

First Results from the Double Chooz Reactor Anti-neutrino Experiment

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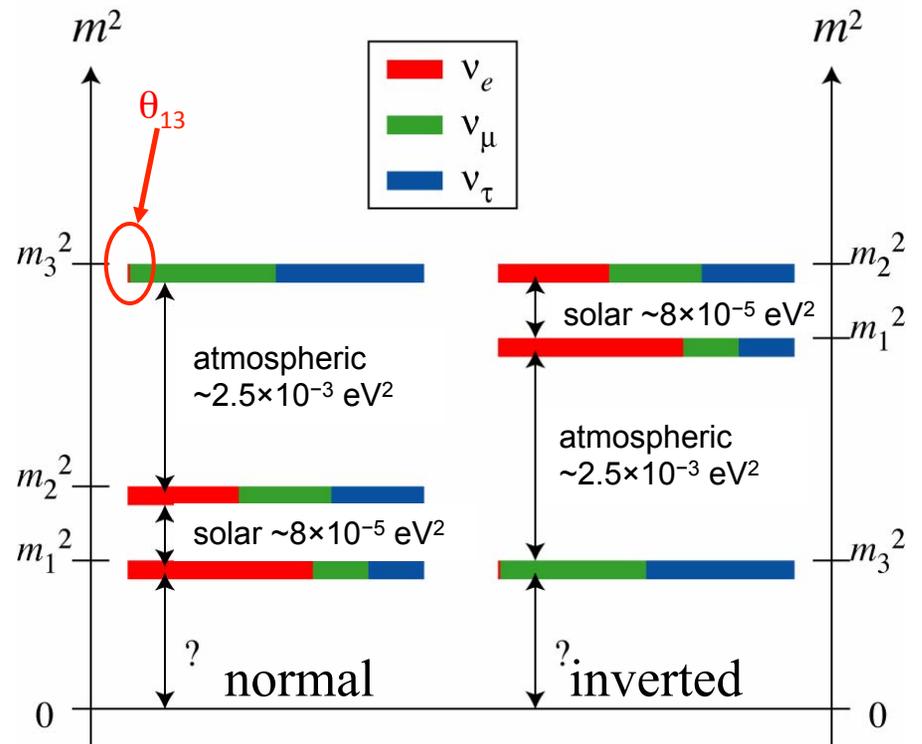


Joint Experimental-Theoretical Seminar, Fermilab, November 18, 2011.

Neutrino Oscillation Results

Missing information in 3x3 ν mixing scheme:

1. What is ν_e component in the ν_3 mass eigenstate, i.e. $\theta_{13} = ?$
-Only know $\theta_{13} < \sim 11^\circ$.
2. Is the $\mu - \tau$ mixing maximal?
-Only know $\sin^2 2\theta_{23} > 0.90$.
3. What is the mass hierarchy?
-Normal or inverted?
4. Do neutrinos exhibit CP violation, i.e. is $\delta_{CP} \neq 0$?



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} \text{Big} & \text{Big} & \text{Small?} \\ \text{Big} & \text{Big} & \text{Big} \\ \text{Big} & \text{Big} & \text{Big} \end{pmatrix}$$

$$= \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}$$

$\theta_{12} \sim 30^\circ$ $\sin^2 2\theta_{13} < 0.11$ at 90% CL $\theta_{23} \sim 45^\circ$

Experimental Methods to Measure θ_{13}

- Long-Baseline Accelerators: Appearance ($\nu_{\mu} \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5 \times 10^{-3} \text{ eV}^2$
 - Look for appearance of ν_e in a pure ν_{μ} beam vs. L and E
 - Use near detector to measure background ν_e 's (beam and misid)

NOvA:

$\langle E_{\nu} \rangle = 2.3 \text{ GeV}$
 $L = 810 \text{ km}$



T2K:

$\langle E_{\nu} \rangle = 0.7 \text{ GeV}$
 $L = 295 \text{ km}$



- Reactors: Disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) at $\Delta m^2 \approx 2.5 \times 10^{-3} \text{ eV}^2$
 - Look for a change in ν_e flux as a function of L and E
 - Look for a non- $1/r^2$ behavior of the $\bar{\nu}_e$ rate
 - Use near detector to measure the un-oscillated flux

Double Chooz:

$\langle E_{\nu} \rangle = 3.5 \text{ MeV}$
 $L = 1100 \text{ m}$



Accelerator vs Reactor Experiment

Long-Baseline Accelerator Appearance Experiments

θ_{13} probed by measuring electron neutrino appearance from accelerator produced muon neutrinos.

Need to have an L and E such that interference between solar and atmospheric scales can be seen

Oscillation probability complicated and dependent not only on θ_{13} but also:

1. CP violation parameter (δ)
2. Mass hierarchy (sign of Δm_{31}^2)
3. Size of $\sin^2 \theta_{23}$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31}^2$$

$$+ \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2$$

$$+ \cos \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos \Delta_{32} \left(\frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31} \right) \left(\frac{\sin(aL)}{(aL)} \Delta_{21} \right)$$

$$+ \sin \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin \Delta_{32} \left(\frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31} \right) \left(\frac{\sin(aL)}{(aL)} \Delta_{21} \right)$$

⇒ These extra dependencies are both a “curse” and a “blessing” since they will let us measure CP violation if θ_{13} is big enough.

Accelerator vs Reactor Experiment

Reactor Disappearance Experiments

θ_{13} probed by measuring the disappearance of reactor produced electron anti-neutrinos.

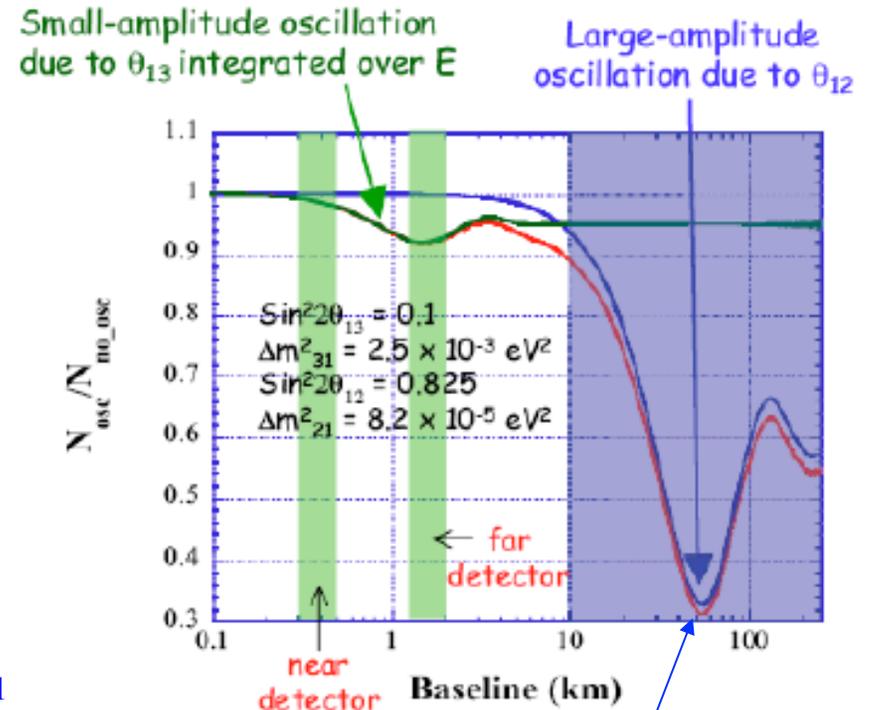
- For θ_{13} need to work at an L/E matched to the atmospheric Δm^2 .
- Reactors used in θ_{12} range as well: need to work at an L/E matched to the solar Δm^2 i.e. Kamland measurement at solar Δm^2 .

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$$

$$\Delta_{ij} \equiv 1.27 \Delta m_{ij}^2 L / E$$

L(km), E(MeV), m(10^{-3} eV)

⇒ Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation



Another large detector here for precise θ_{12} measurement?

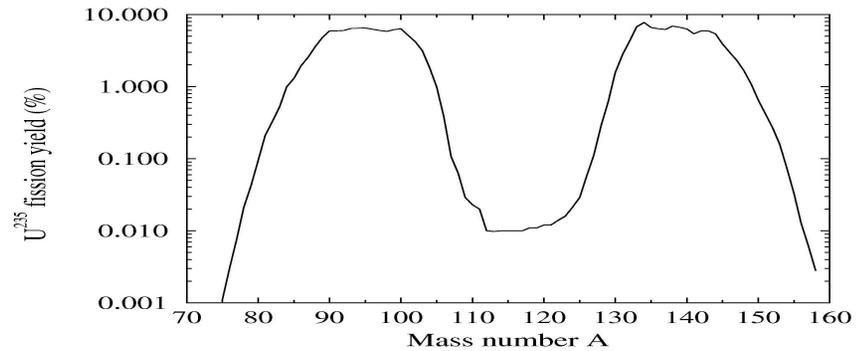
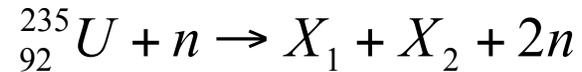
Nuclear Reactors as $\bar{\nu}_e$ Sources

What creates the reactor $\bar{\nu}_e$'s ?

- Typical modern nuclear power reactor has a thermal power of: $P_{\text{therm}} = 3.8 \text{ GW}$
 - About 200 MeV / fission of energy is released in fission of ^{235}U , ^{239}Pu , ^{238}U , and ^{241}Pu .
 - The resulting fission rate, f , is thus: $f = 1.2 \times 10^{20}$ fissions/s
 - At $6\bar{\nu}_e$ / fission the resulting yield is: $7.1 \times 10^{20} \bar{\nu}_e / \text{s}$.

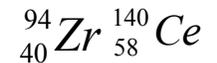
Using e^- spectra measurements for ^{235}U , ^{239}Pu , and ^{241}Pu
 Can calculate the ν_e flux to 2-3%.

Example: ^{235}U fission

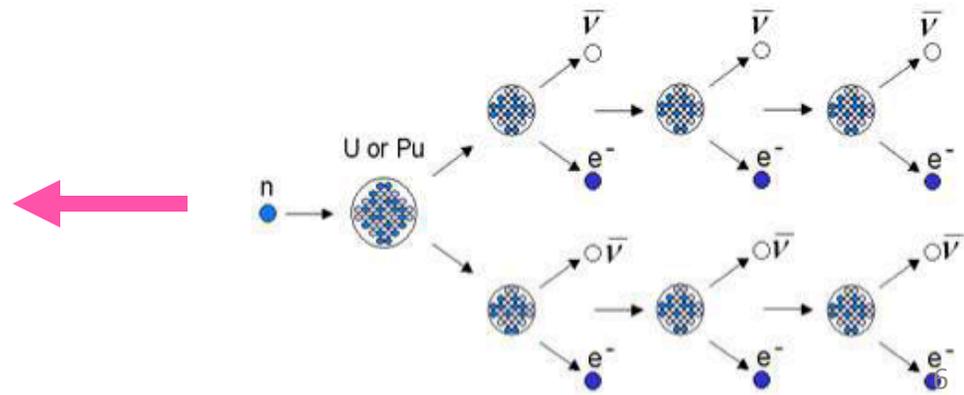


Most likely A from $\Rightarrow {}^{94}\text{Zr}$ ${}^{140}\text{Ce}$
 ^{235}U fission

→ on average 6 n have to β -decay to 6 p to reach stable matter:

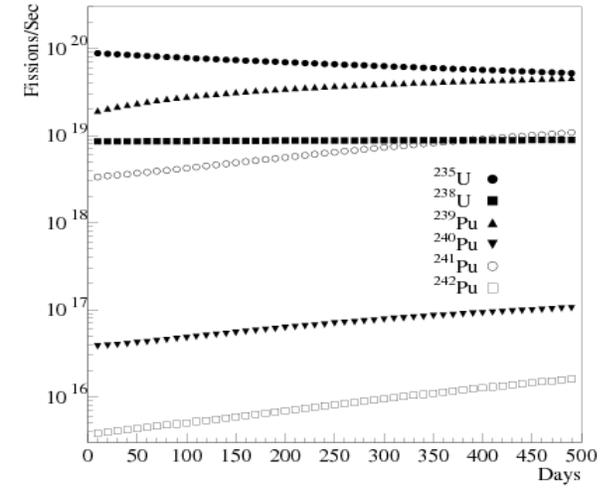


→ on average 1.5 ν_e are emitted with energy $> 1.8 \text{ MeV}$

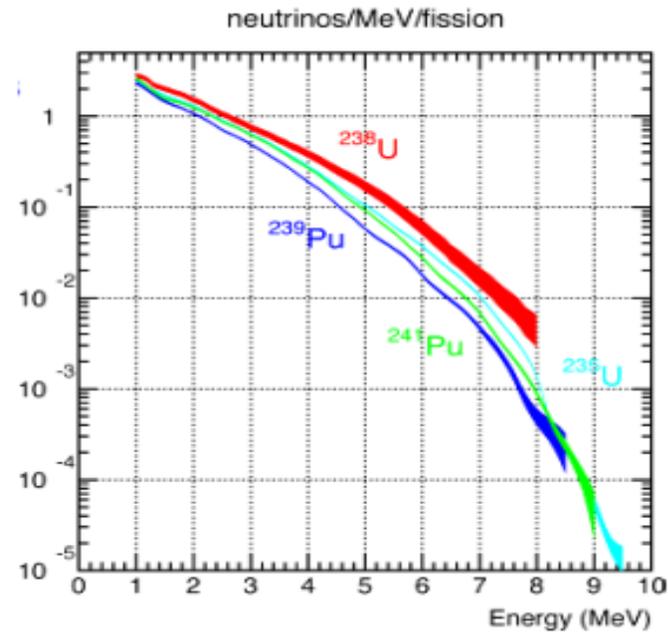
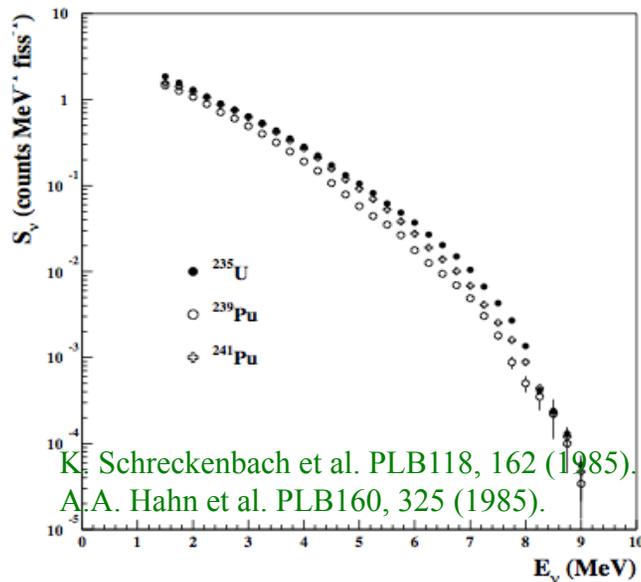


$\bar{\nu}_e$ Flux Calculation

- To perform this calculation correctly one must
 - consider ^{235}U , ^{238}U , ^{239}Pu , and ^{241}Pu ($> 99.5\%$ $\bar{\nu}_e$ flux),
 - account for all possible β branches.
 - correct for evolution of the reactor core over the fuel cycle.

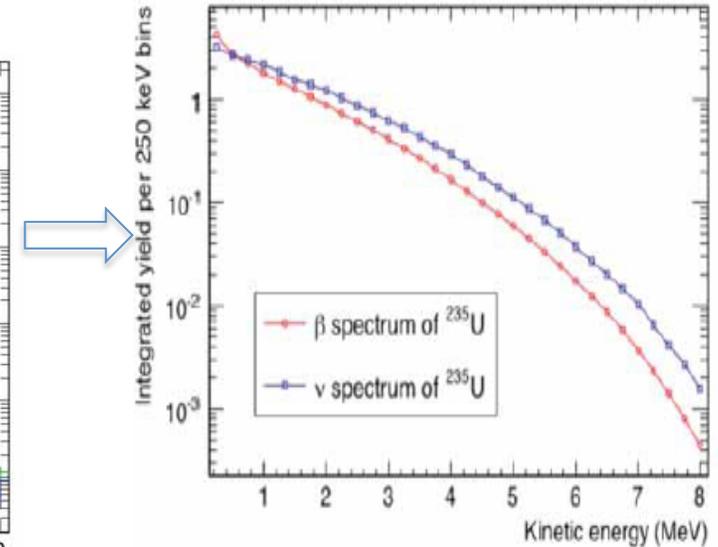
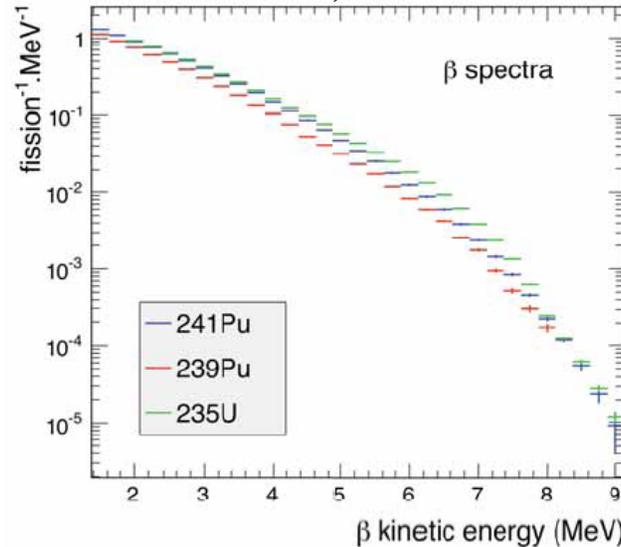


- Measurement the β spectra of fission-ing of U-235, Pu-239, and Pu-241 samples by thermal neutrons performed at ILL, and converted to neutrino spectra.
- U-238 relies on theoretical calculation, 10% uncertainty (P. Vogel et al., PRC24, 1543 (1981)). U-238 contributes (7-10)% fissions.



Conversion from Electron to anti-Neutrino Spectra

- Old method (A. Schreckenbach et al.) used 30 effective β branches.



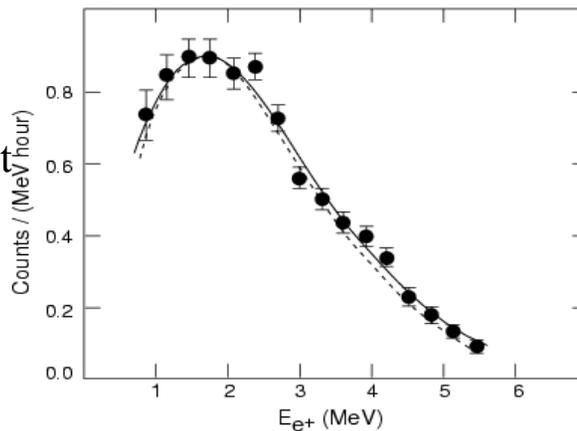
- Comparison of prediction to observation:

Example:

Goesgen Experiment

Solid: Fit to Data

Dashed: Prediction from β spectrum



Another example

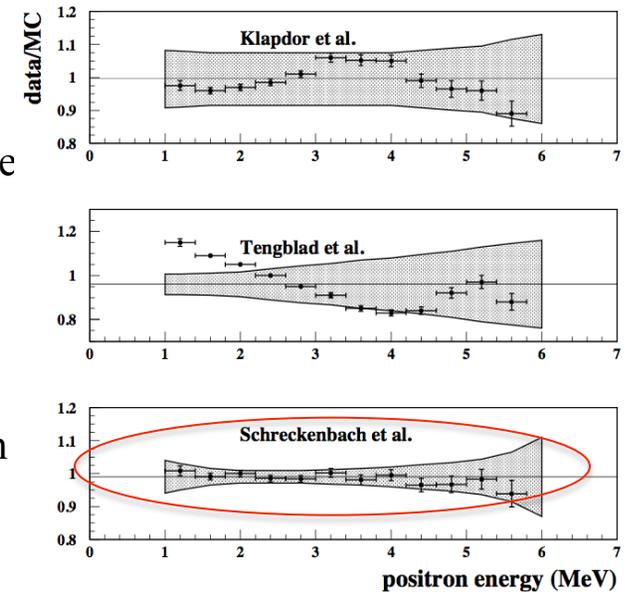
Bugey 3 Exp:

comparison to

three different

reactor spectrum

models.



Flux and Energy Spectrum known at $\sim 2-3\%$ level

\rightarrow Reactors used as “calibrated sources” of $\bar{\nu}$ ’s

Normalization error $\sim 1.9\%$.

Energy dependent (shape) error from 1.34% at 3 MeV to 9.2% at 8 MeV.

Reactor $\bar{\nu}$ Flux and “Reactor Anomaly”

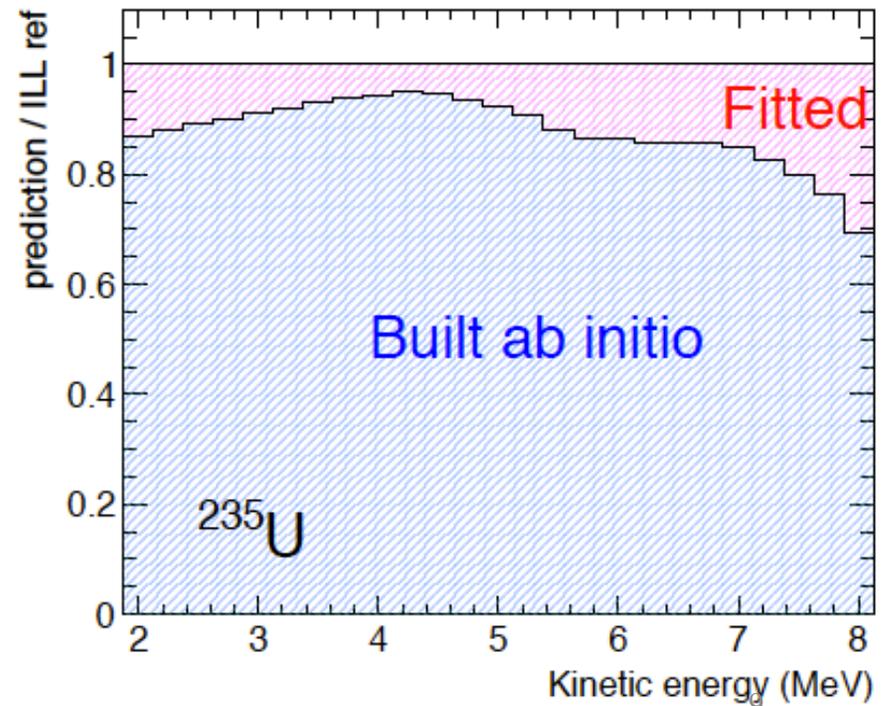
Th. A. Mueller et al. “Improved Predictions of Reactor Antineutrino Spectra,”
Phys. Rev. C83, 054615, 2011.

Mueller et al. have refined method to go from measured ^{235}U , ^{239}Pu , and ^{241}Pu β^- spectra (at ILL) to neutrino spectra.

New method uses all available information on measured nuclei from nuclear databases (~90% info from data bases, remaining ~10% fitted with 5 effective branches)

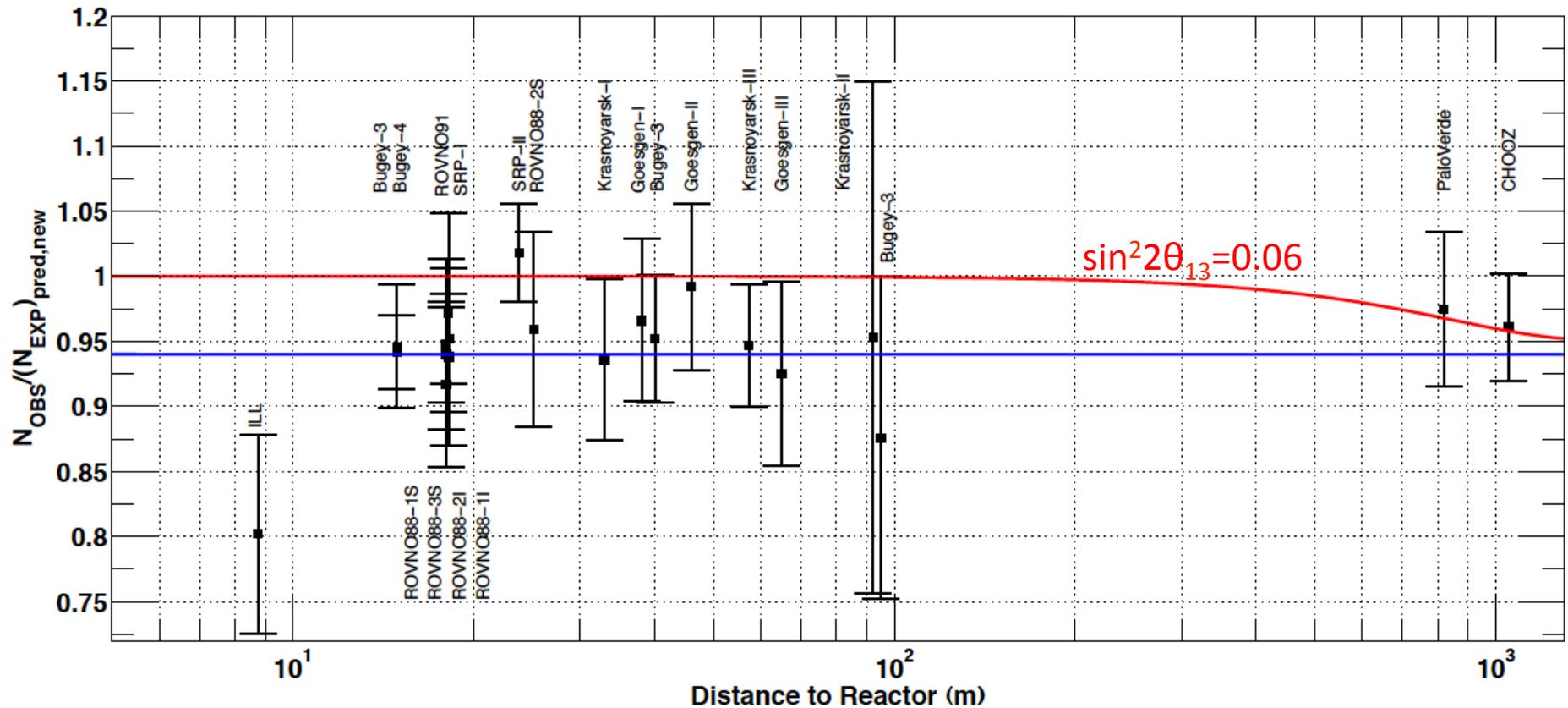
The result is a +3% increase in neutrino flux, on average.

Trend independently confirmed by P. Huber, arXiv:1106.0687.



Reactor $\bar{\nu}$ Flux and “Reactor Anomaly”

G. Mention et al., “The Reactor Antineutrino Anomaly,” Phys. Rev. D83, 073006, 2011.



For $L < 100\text{m}$, accounting for correlations, results is $N_{\text{OBS}}/N_{\text{EXP}} = 0.937 \pm 0.027$

Possible bias or new physics at short baselines?

Results are compatible with 4th, sterile neutrino state with $\Delta m^2 > \sim 1 \text{ eV}^2$ and $\sin^2 2\theta \sim 0.1$ (i.e. MiniBooNE/LSND, etc).

$\bar{\nu}$ Detection Technique

- The reaction process is inverse β^- decay followed by neutron capture
 - Two part coincidence signal is crucial for background reduction.



$\hookrightarrow n$ capture

- Positron energy spectrum implies the neutrino spectrum ($e^+e^- \rightarrow \gamma\gamma$)

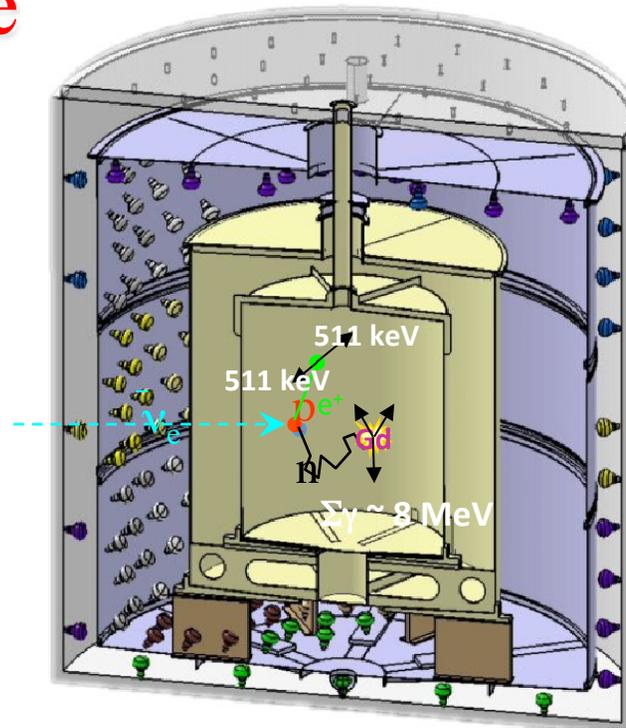
$$E_\nu = E_{vis} + 1.8 \text{ MeV} - 2m_e$$

- The scintillator may be doped with gadolinium to enhance capture

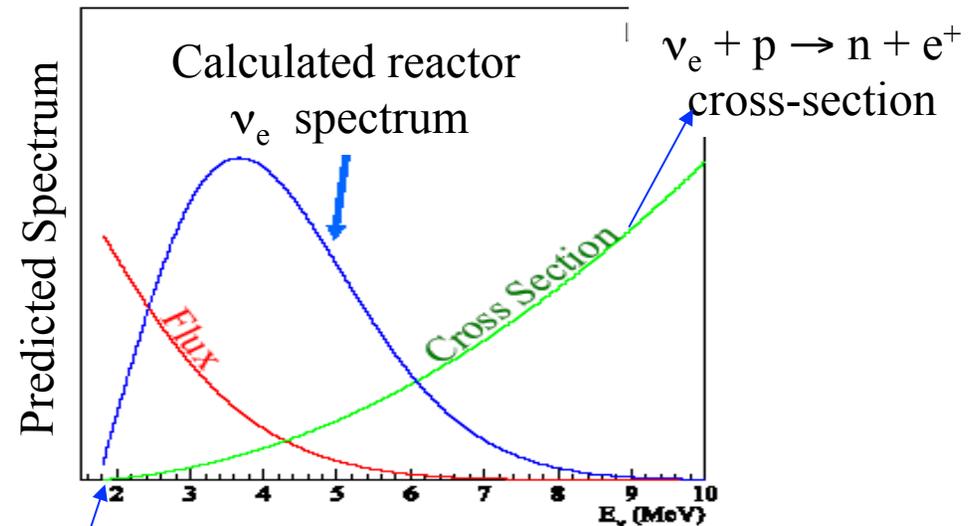


- Cross accurate to 0.2%

P. Vogel and J. Beacom,
 Phys.Rev.D60:053003,1999
 A. Strumia and F. Vissani,
 Phys.Lett.B564:42-54,2003;



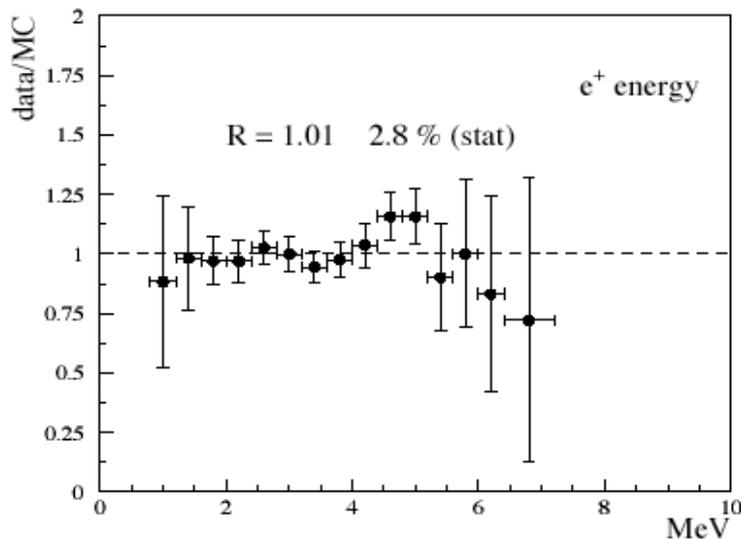
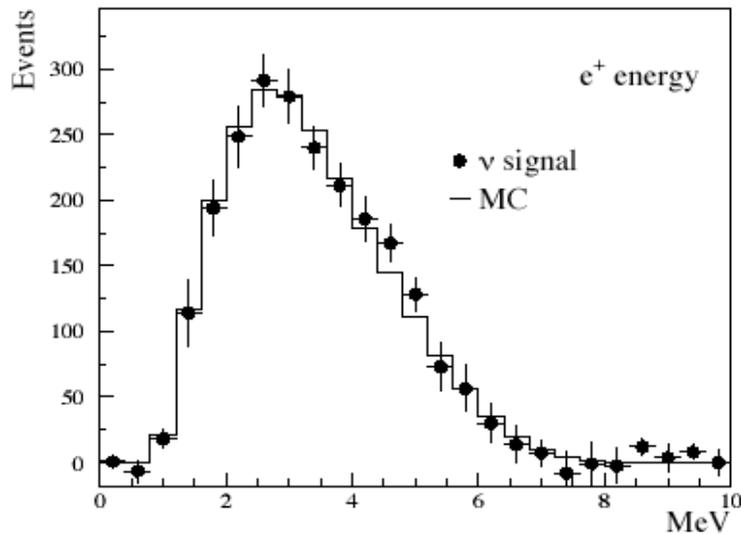
Signal = Positron signal + Neutron Signal (within a few capture times)



Neutrinos with $E < 1.8 \text{ MeV}$ are not detected.

Best Reactor θ_{13} Limit: CHOOZ Experiment

The current best limit for $\sin^2 2\theta_{13}$ is from the CHOOZ experiment: was built to find out if the atmospheric neutrino deficit was due to θ_{12} , and the measurement of θ_{13} was an unexpected by-product.



-One detector experiment

→Major systematic was reactor flux

-Large singles rate due to radioactivity of PMTs

→problem was scintillator reaching out to tubes

-Detector stability issues with scintillator

→light output decreasing with $\tau=720$ days

-Small fiducial mass:

→CHOOZ: 5 tons @ 1km, 5.7 GW

~2.2 events/day/ton with 0.2-0.4 bkgd events/day/ton

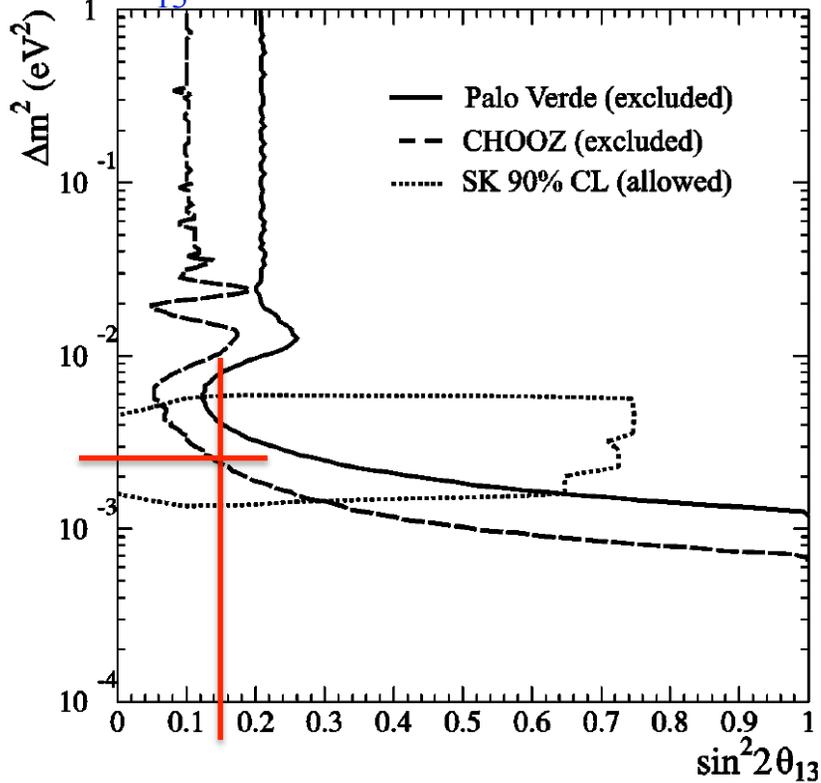
~3600 ν events total

parameter	relative error (%)
reaction cross section	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%

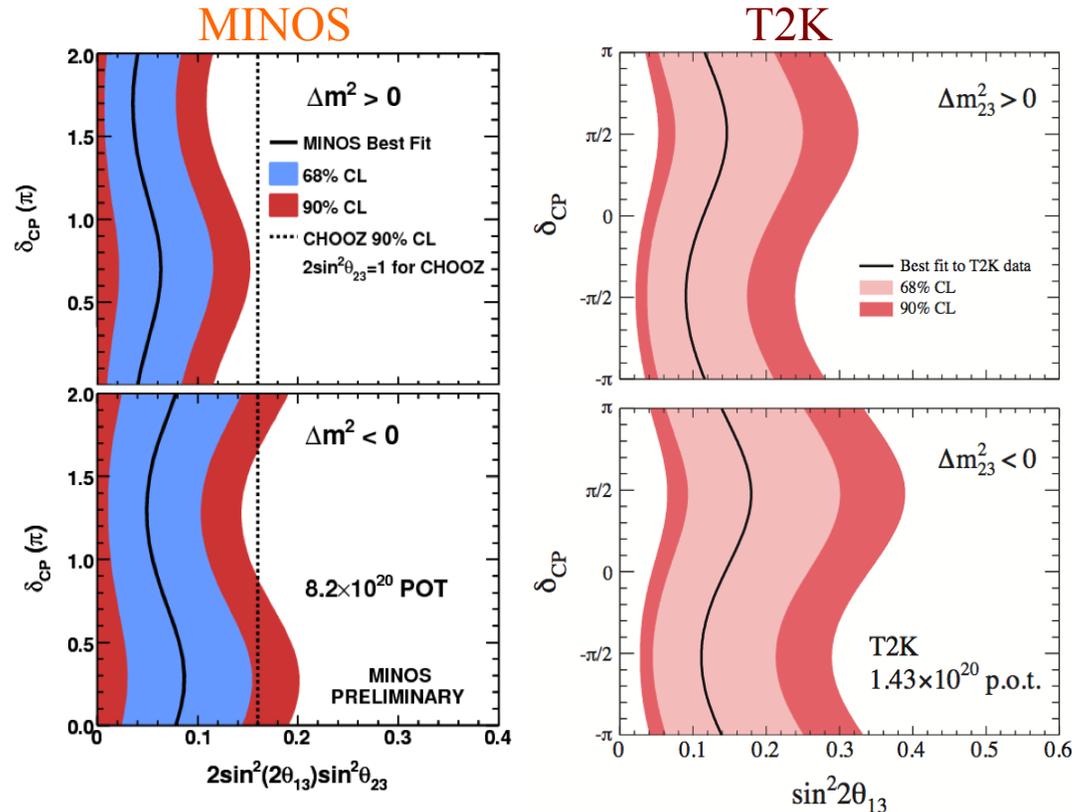
CHOOZ : $R_{\text{osc}} = 1.01 \pm 2.8\% (\text{stat}) \pm 2.7\% (\text{syst})$

Best Reactor θ_{13} Limit and New Results

$\sin^2 2\theta_{13} < 0.15$ for $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$



Recent Accelerator Results



MINOS: For $\delta_{CP} = 0$, $\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$, the allowed values $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ at 90%CL:

Normal: 0 to 0.12, central value: 0.04

Inverted: 0 to 0.19, central value: 0.08

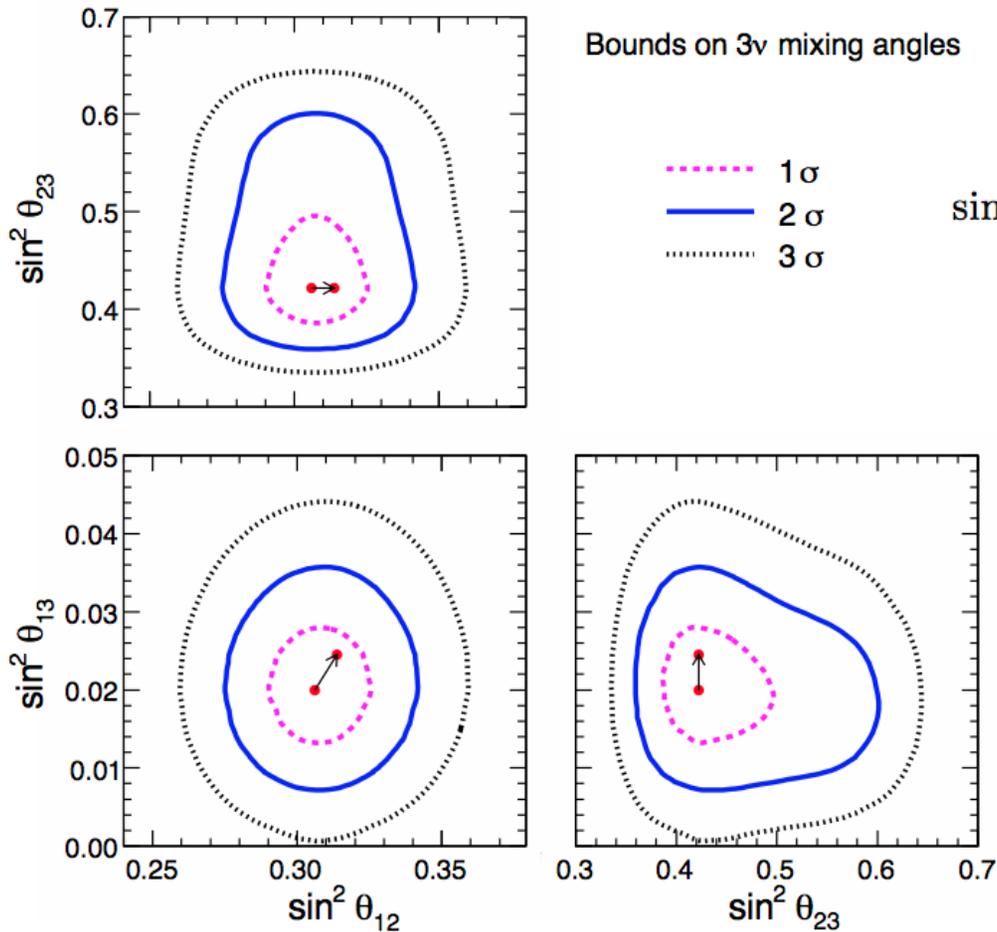
T2K: For $\delta_{CP} = 0$, $\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{23} = 1$, allowed values $\sin^2 2\theta_{13}$ at 90% CL

Normal: 0.03 to 0.28, central value: 0.11

Inverted: 0.04 to 0.34, central value: 0.14

Non-zero θ_{13} Evidence

Recent global analysis fit for $\sin^2\theta_{13}$ vs $\sin^2\theta_{12}$: Fogli et al. arXiv: 1106.6028[hep-ph]



$$\sin^2 \theta_{13} = \begin{cases} 0.021 \pm 0.007, & \text{old reactor fluxes} \\ 0.025 \pm 0.007, & \text{new reactor fluxes} \end{cases} \quad (1\sigma)$$



$$\sin^2 2\theta_{13} = \begin{cases} 0.082 \pm 0.028 \\ 0.098 \pm 0.028 \end{cases}$$

Is θ_{13} non-zero and within a reach?
 → Need new sensitive experiments to confirm!

How can one improve on CHOOZ Experiment and possibly measure θ_{13} ?

Add an identical near detector → eliminate dependence on reactor flux.

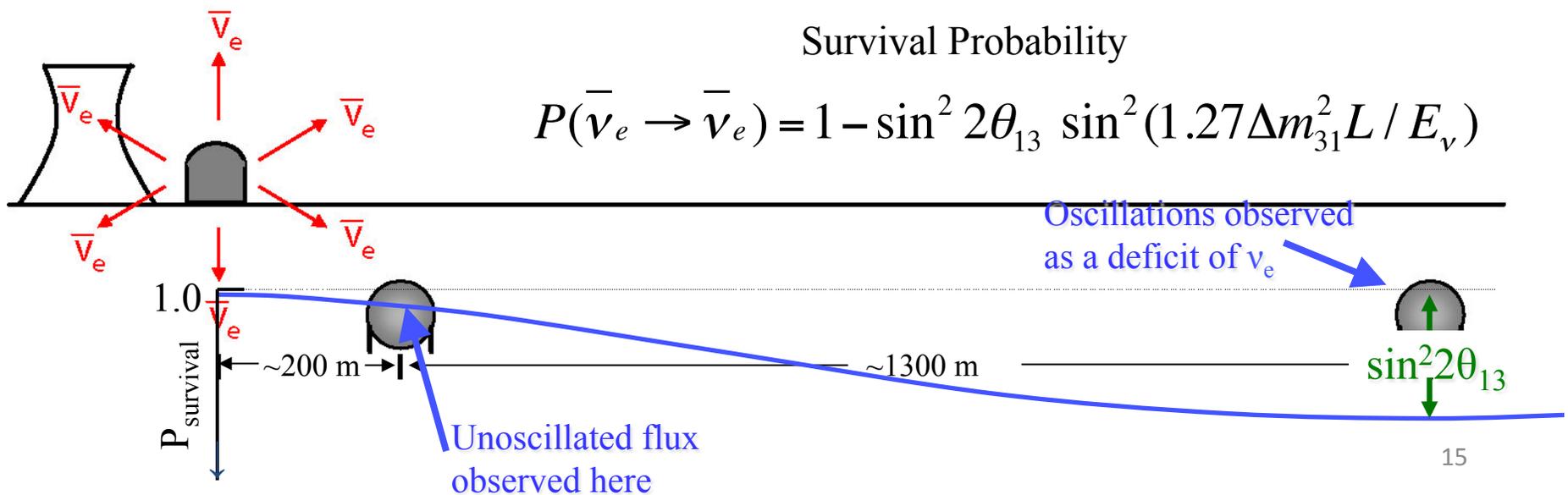
Optimize baseline → near detector close to reactors, far detector at oscillation maximum.

Use larger detectors with reduced systematics uncertainties → improved statistics, minimize systematics.

High power reactor sites → improved statistics.

Reduce backgrounds → go deeper and use active veto systems.

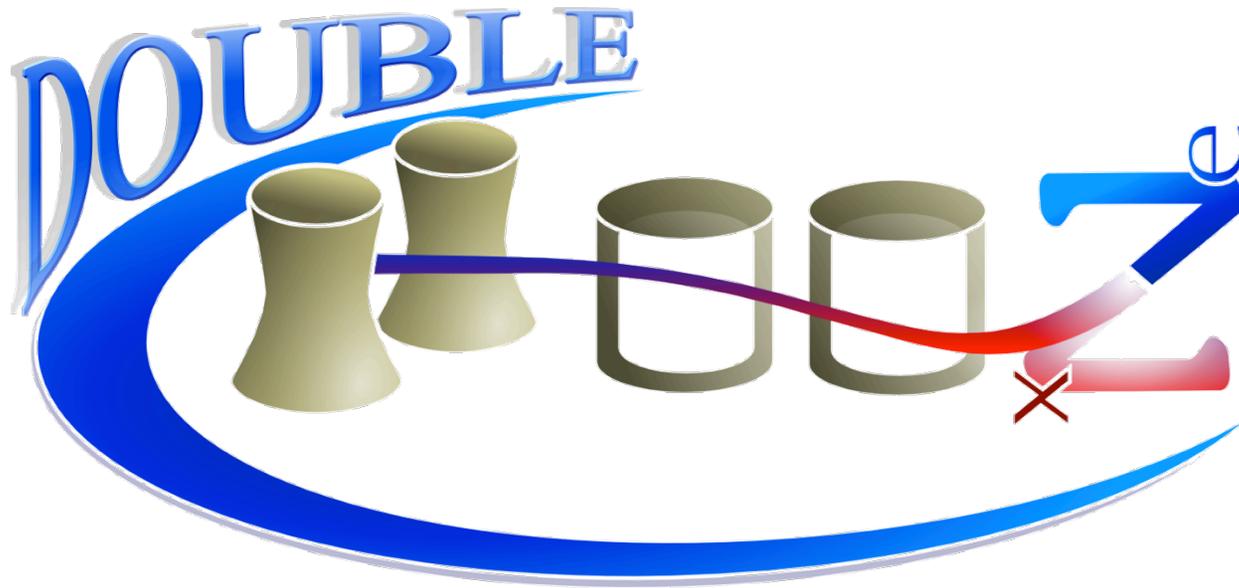
Stable scintillator → eliminate aging effects.



New Multi-detector θ_{13} Reactor Experiments

Experiment	GW_{th}	Distance Near/Far (m)	Shielding Near/Far (mwe)	Target Mass (tons)	Sensitivity $\sin^2 2\theta_{13}$ (90% c.l.)	Status
Double Chooz (France)	8.4	390/1050	115/300	8/8	0.03	Data taking with far; near end 2012
RENO (Korea)	17.3	290/1380	120/450	16/16	0.02	Start mid- 2011
Daya Bay (China)	17.4	360(500)/ 1985(1615)	260/910	2×2×20 (N) 4×20 (F)	0.01	Started 1 near.

- Many similarities in detector design and analysis strategy
- Differences in sensitivity come mainly from statistics (mass, reactor power), baseline optimization, and multiple detector sites (for Daya Bay)



Double Chooz Reactor Experiment in Ardennes, France

Double Chooz Collaboration



Brazil

CBPF
UNICAMP
UFABC



France

APC
CEA/DSM/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC
ULB



Germany

EKU Tübingen
MPIK Heidelberg
TU München
U. Aachen
U. Hamburg



Japan

Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima InstTech.



Russia

INR RAS
IPC RAS
RRC Kurchatov



Spain

CIEMAT-Madrid



UK

Sussex



USA

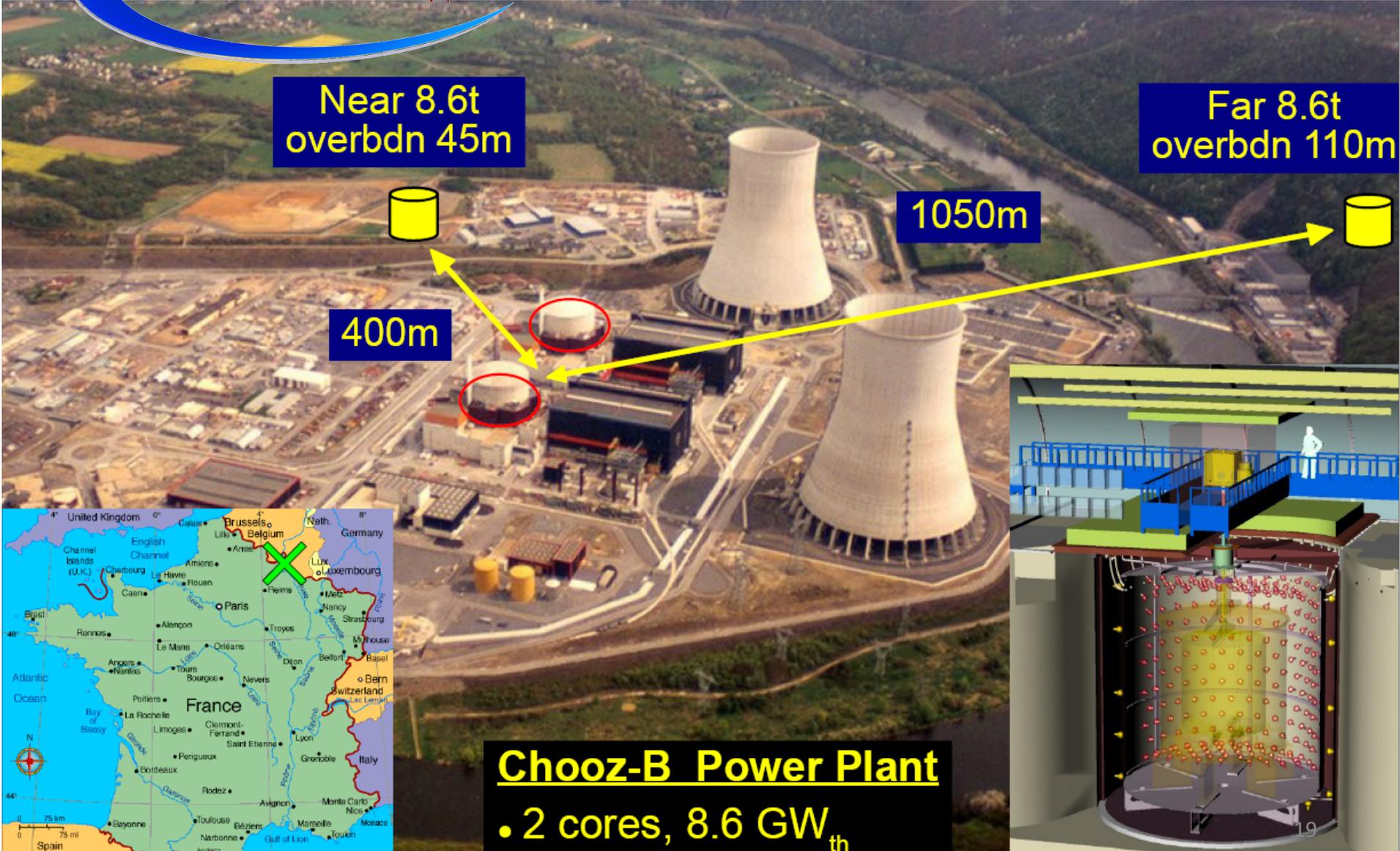
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
Sandia National
Laboratories
U. Tennessee

Spokesperson: H. de Kerret (CNRS/IN2P3-APC)

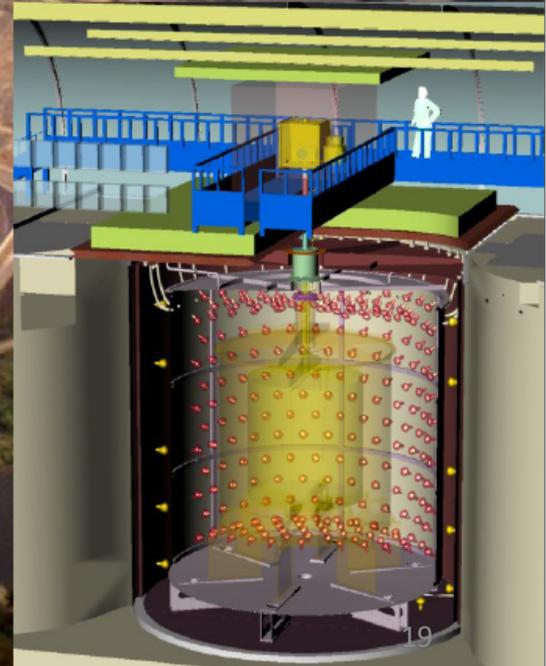
Project Manager: Ch. Veyssi re (CEA-Saclay)

Web Site: www.doublechooz.in2p3.fr/





Chooz-B Power Plant
 • 2 cores, 8.6 GW_{th}

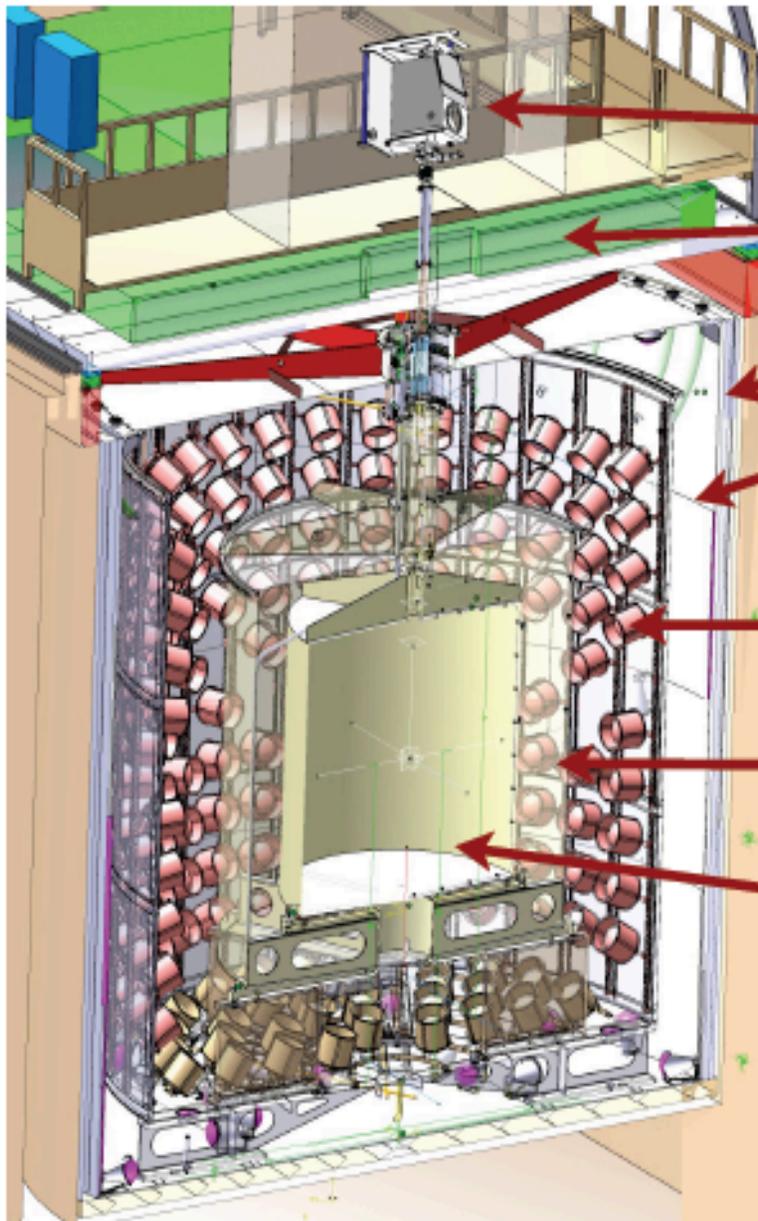


Double Chooz Timeline

Major Milestones:

- May 2008 - October 2010 → Far detector construction.
- December 2010 → Far detector filling completed.
- April 2011 → Far detector commissioned.
- April 2011 → Start physics data taking with far detector.
- April 2011 → Near laboratory construction started.
- July 2011 → Outer veto commissioned.
- November 2011 → First Data Analysis Complete.
- June 2012 → Near laboratory expected delivery.
- Beginning 2013 → Data taking with two detectors.

Improved Detector Design



Calibration glove box

Outer Veto: plastic scintillator strips

Shielding: steel 15 cm thick

Inner Veto: 90m³ of liquid scintillator
78 8" PMTs

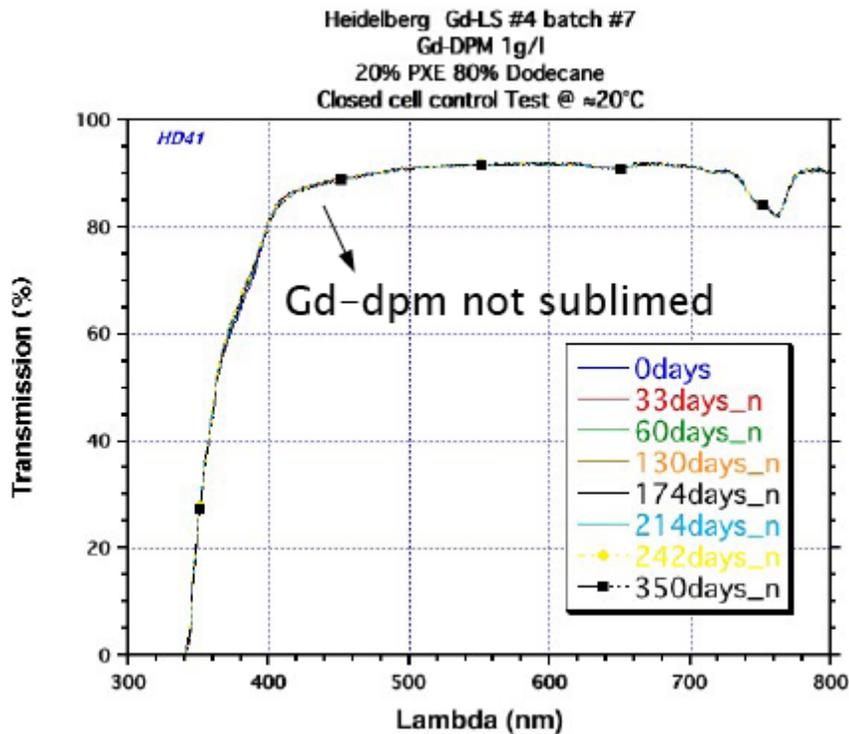
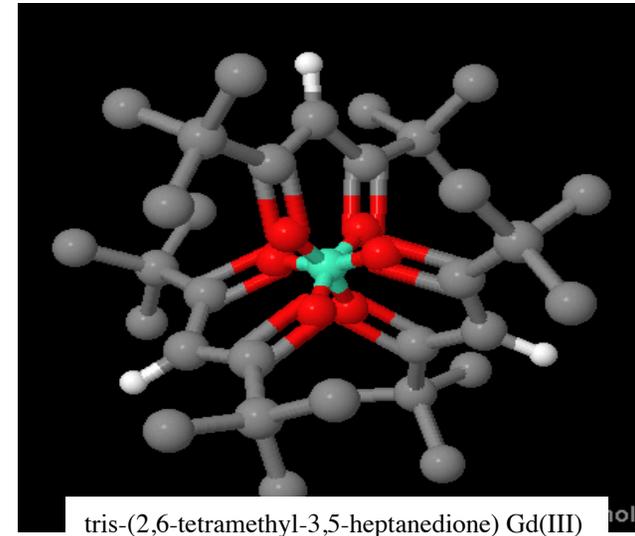
Buffer: 110m³ of non-scintillating
mineral oil
390 10" PMTs

Gamma-Catcher: 22.3m³ of liquid
scintillator

Target: 10.3m³ of liquid scintillator
doped with 1g/L of Gd

Double Chooz Liquid Scintillator

- Target scintillator composed of 20% PXE, 80% Dodecane, PPO, Bis-MSB, Gd(dpm)₃
 - Good stability tested over >5 years
 - Attenuation length >10m @ 430 nm
 - Materials exposed to the target are tested for compatibility
 - 0.1% Gd loading
 - Light yield ~ 7000 ph/MeV

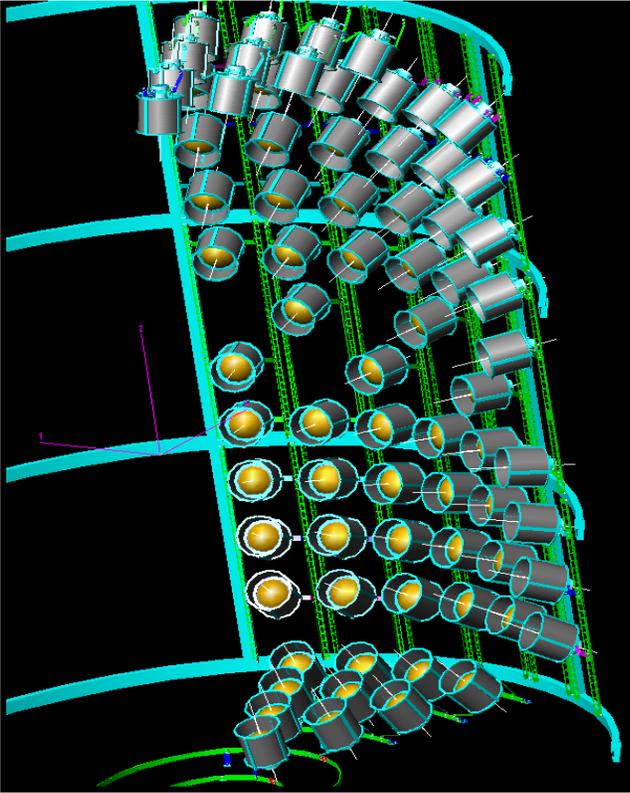


- Gamma Catcher Scintillator composed of 4% PXE, 46% Dodecane, 50% oil, PPO, Bis-MSB.

-Density and light yield matched to the target

- Inner Veto filled with scintillating LAB oil.

Detector Readout



Inner detector:

- 10" Ultra low background tubes.
- 390 PMTs (270 side, 120 top + bottom).
- 13 % coverage.

(see T. Matsubara *et al.* arXiv: 1104.0786 [physics.ins-det])

Inner veto:

- 78 8" PMTs.

- Readout FEE: signal waveforms,
trigger = analog sum $> 0.35\text{MeV}$.

- FADC, 500MHz.

- No dead time.

- Special muon showering electronics.

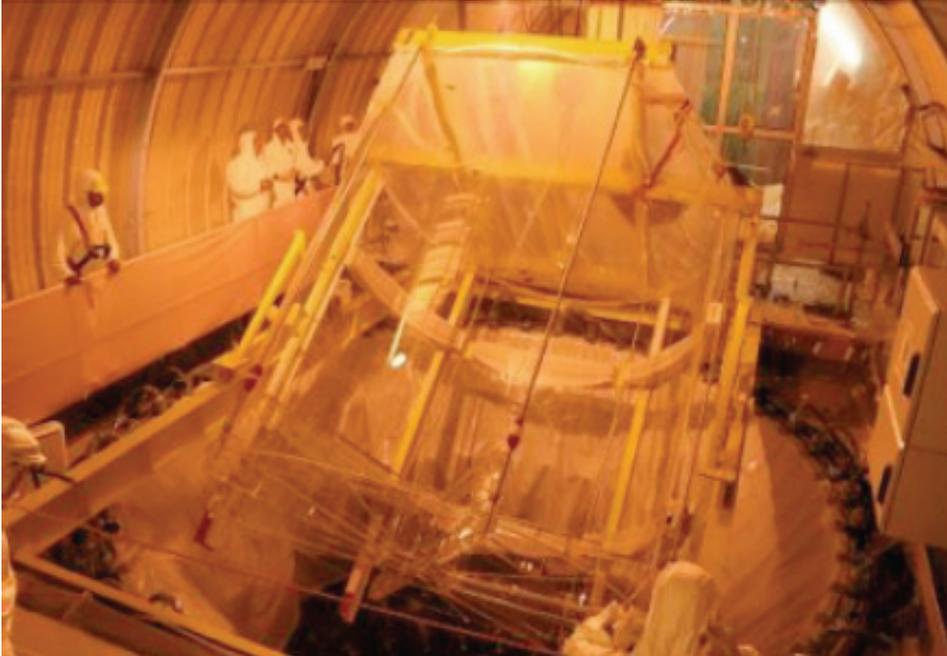
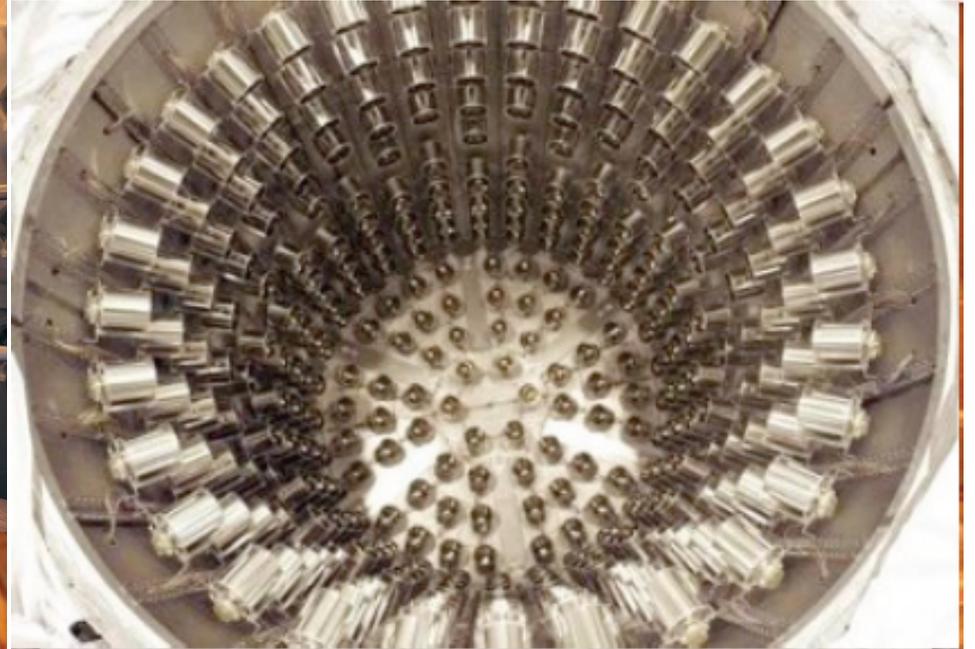
- Special OV FEE.



Far Detector Installation

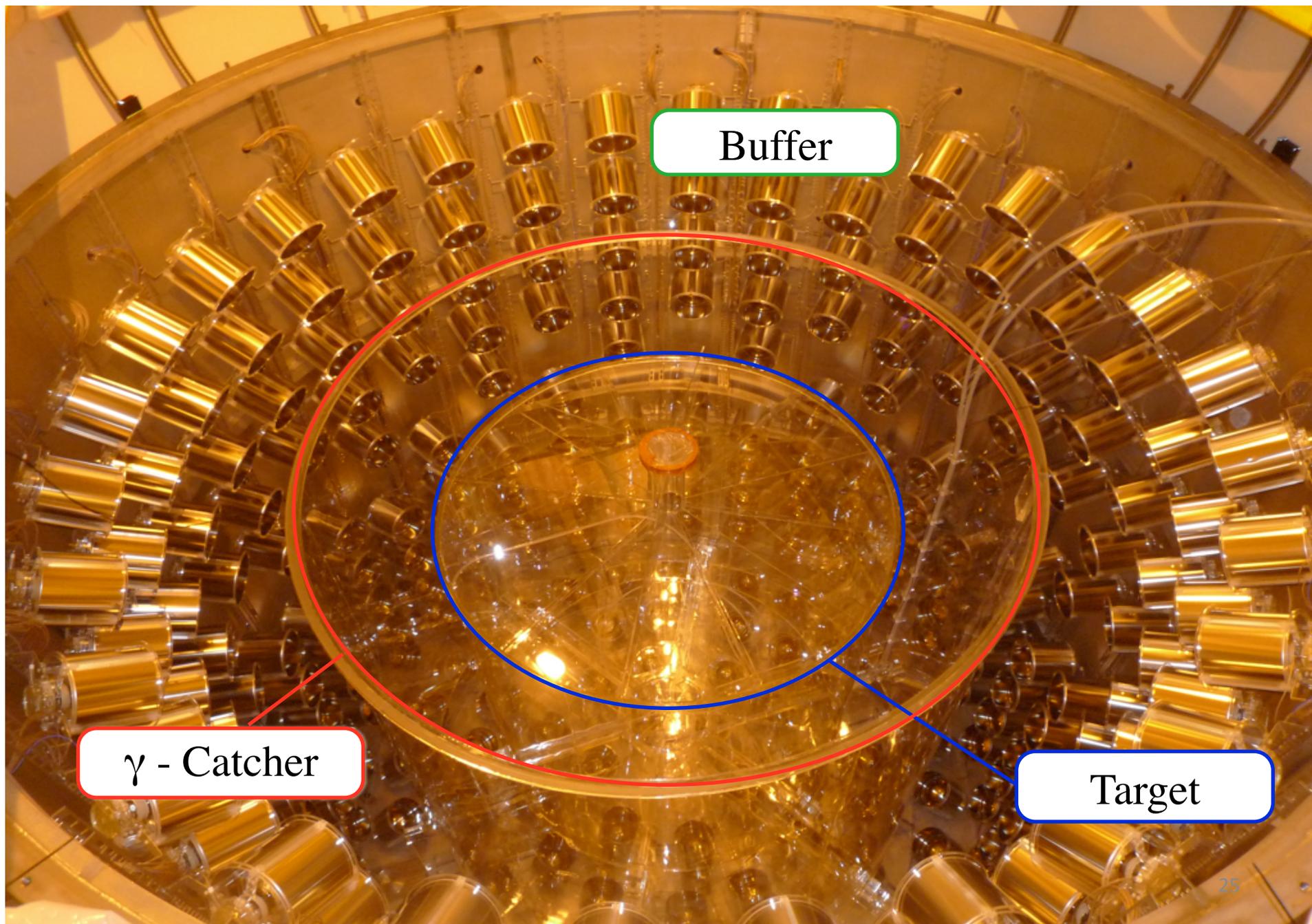


-Inner Detector Buffer and PMTs.



-Acrylic Vessel Instalation.

Far Detector Installation

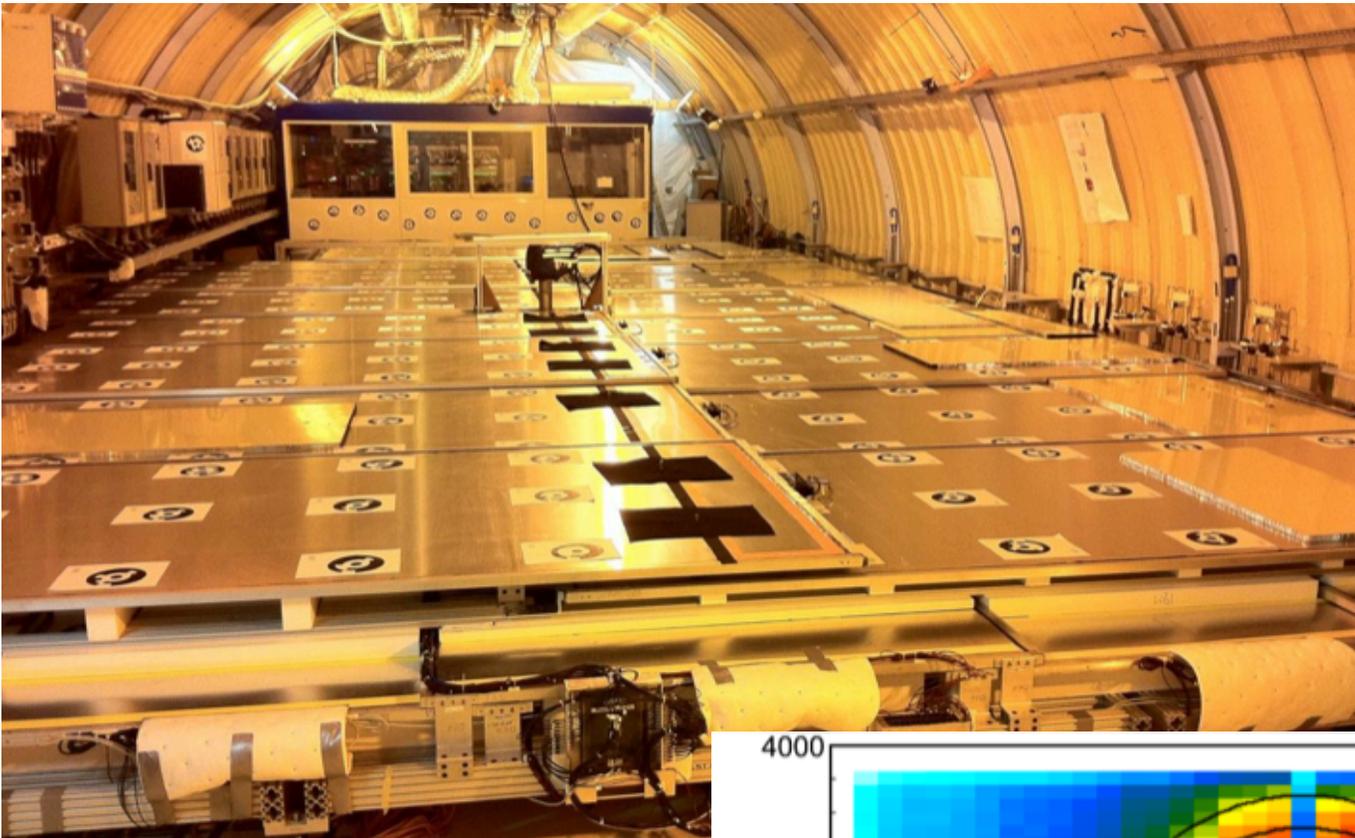


Buffer

γ - Catcher

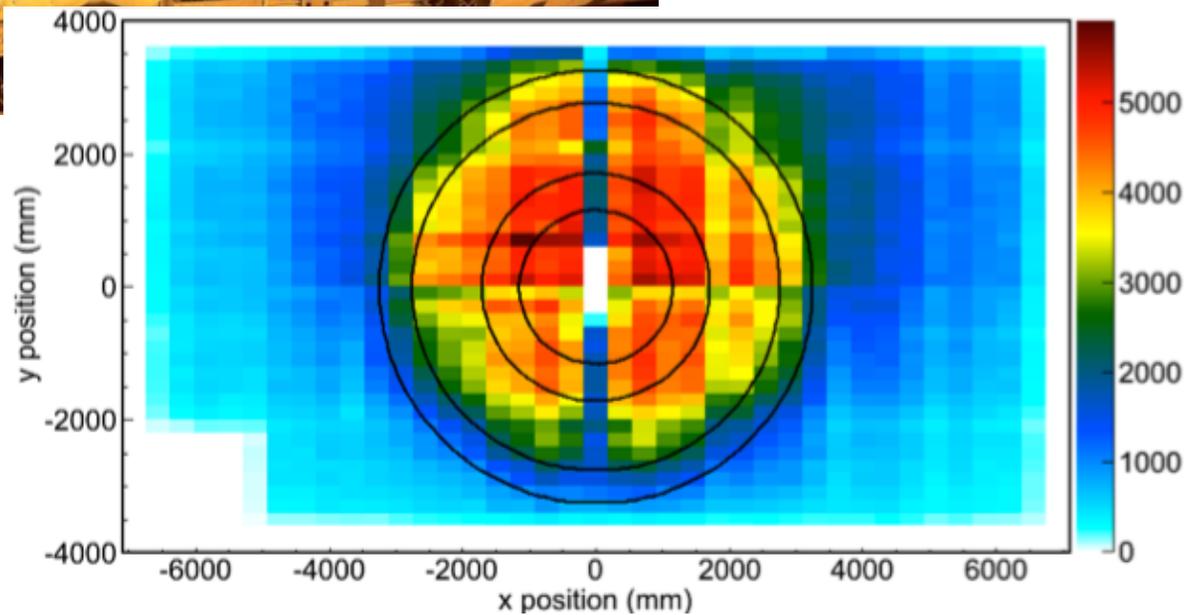
Target

Far Detector Installation



-Outer Veto.

-Muons seen by both the
Outer Veto and the
Inner Detector
-Mountain Shape.



Double Chooz Near Detector Status

- Near Site/Lab Construction started 29th April 2011.
- Lab expected to be ready for physics mid 2012.
- Near Detector ready at the end of 2012.



Double Chooz Near Detector Status

- Near Site/Lab Construction started 29th April 2011.
- Lab expected to be ready for physics mid 2012.
- Near Detector ready at the end of 2012.



Stable Data Taking since April 13th 2011

Number of data taking days: 206 d. (April 13 – November 4).

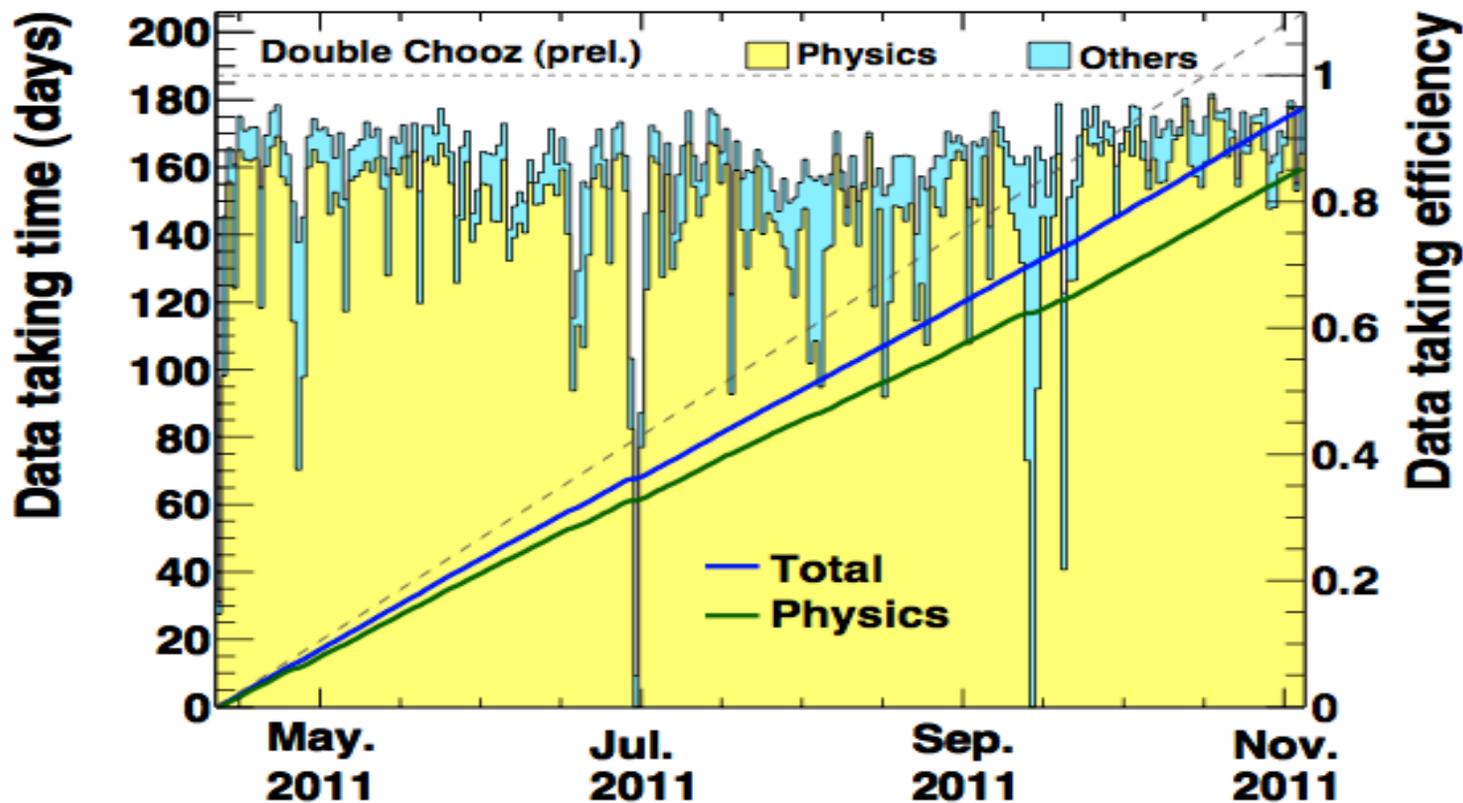
Average data taking efficiency in total: 86.2%.

Average data taking for physics: 77.5%.

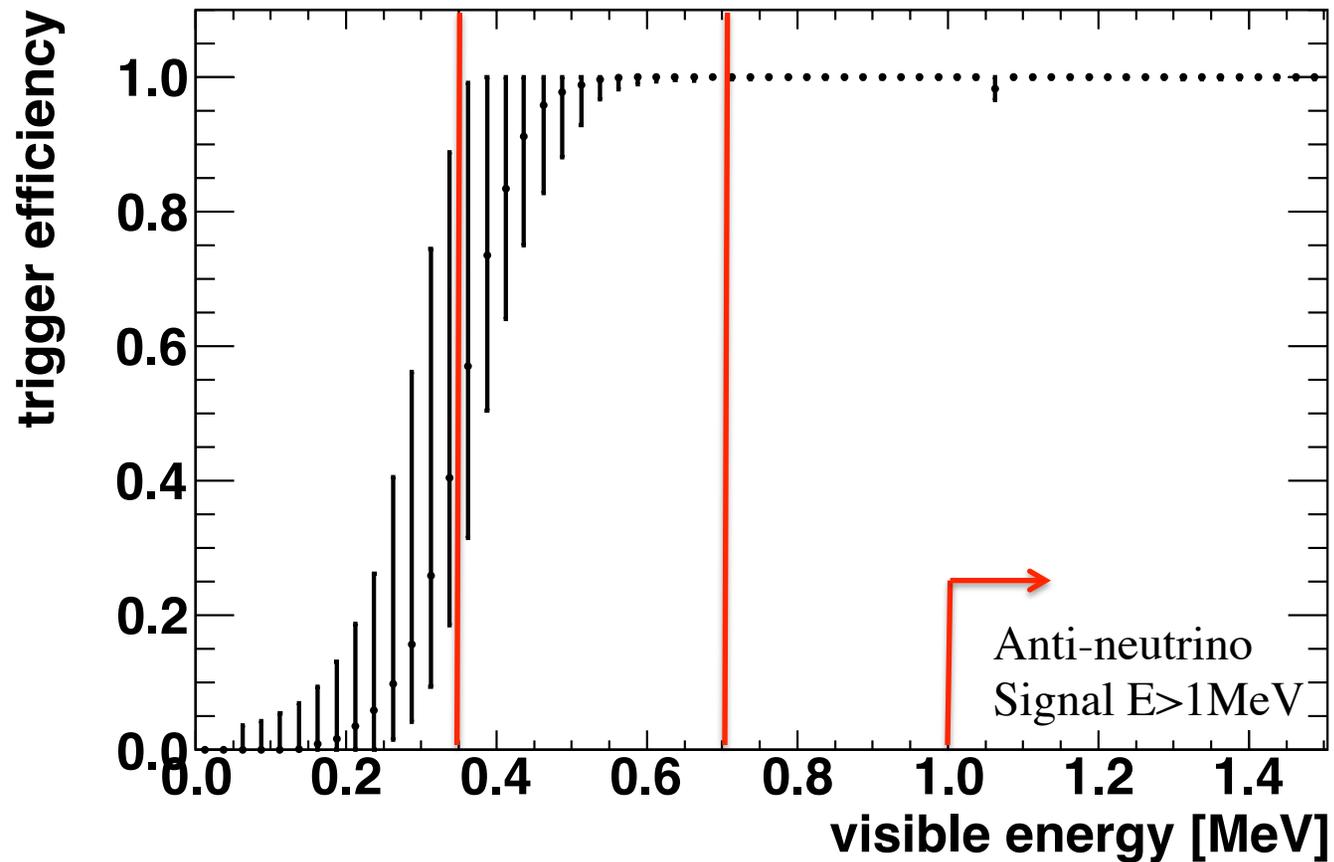
Integrated data taking time in total: 177.4 d.

Integrated data taking time for physics: 159.6 d

First analysis (with muon veto deadtime already subtracted): 96.8 d. (April 13, 2011 to September 18, 2011).



Trigger Efficiency

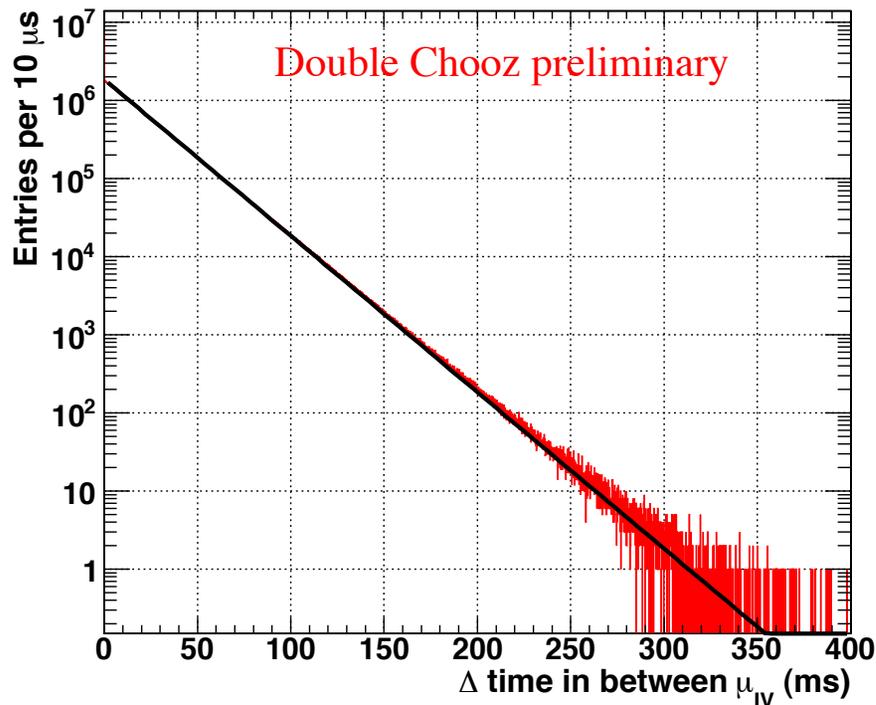


- Error bars (gray band) show systematic uncertainty
- Trigger threshold (defined as 50% efficiency) is 350 keV
- Trigger efficiency is 100% \pm 0.4% above 700 keV

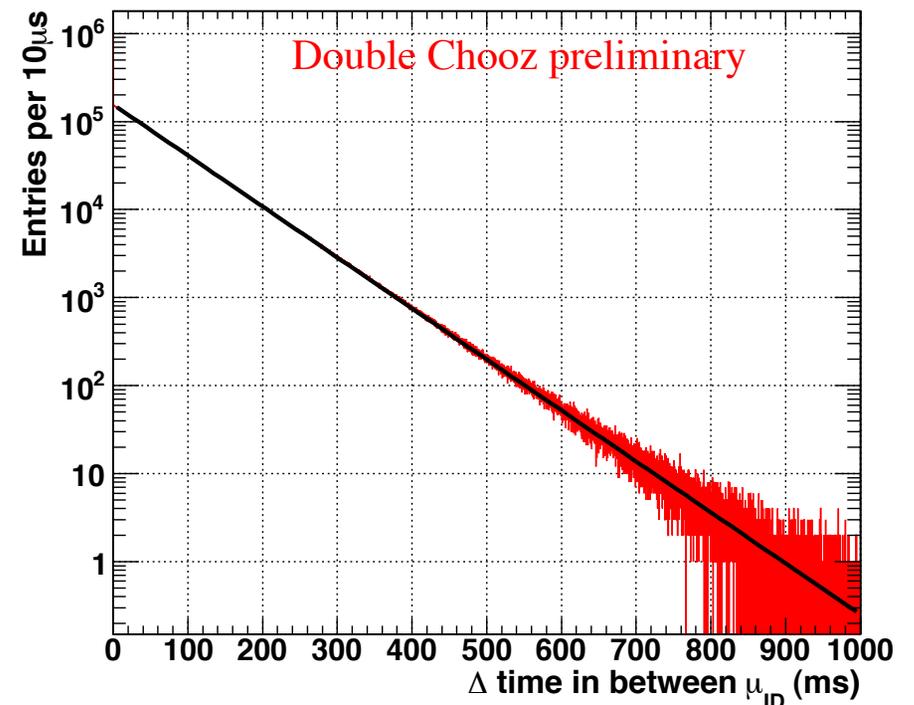
Physics Data: Muons

- Far detector is located 150 m under the hill.
- 46 Hz of muons tagged by Inner Veto.
- 13 Hz of muons tagged by Inner Detector.
- Neutrino search: Remove all events 1msec after muon tagged by large inner-veto or inner-detector energy deposition.

Muon rate in Inner Veto: 46 Hz



Muon rate in Inner Detector: 13 Hz



Physics Data: Spallation Neutrons

-Muon-correlated events in Gd-capture time window (left plot).

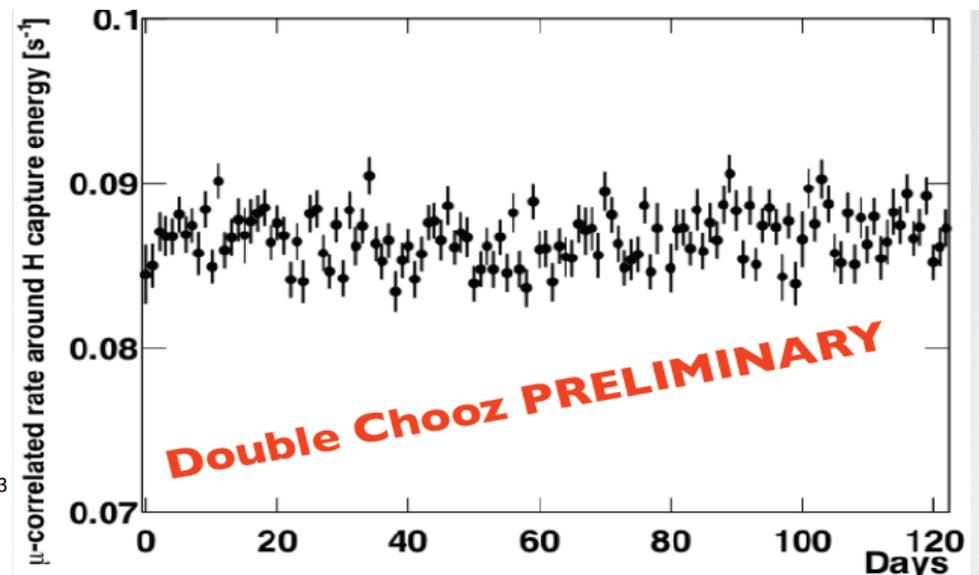
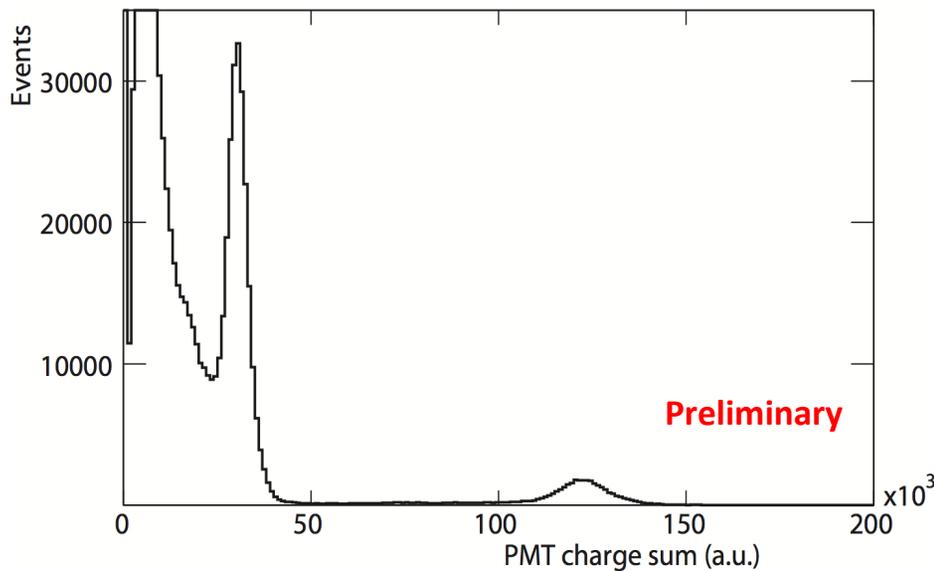
-Mostly spallation neutrons: Peaks of neutron capture on:

Hydrogen (2.2MeV)

Gadolinium (~ 8 MeV).

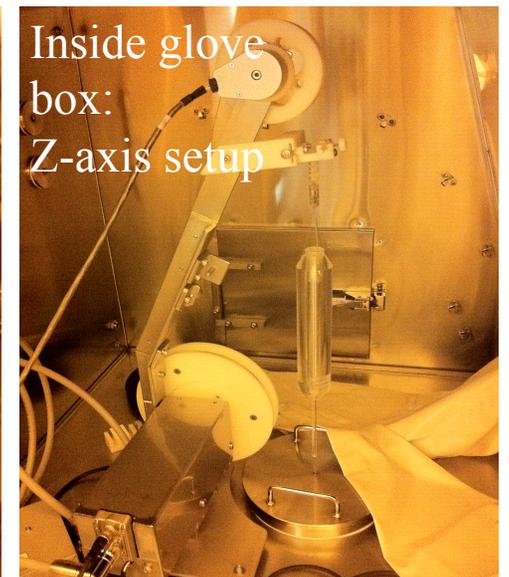
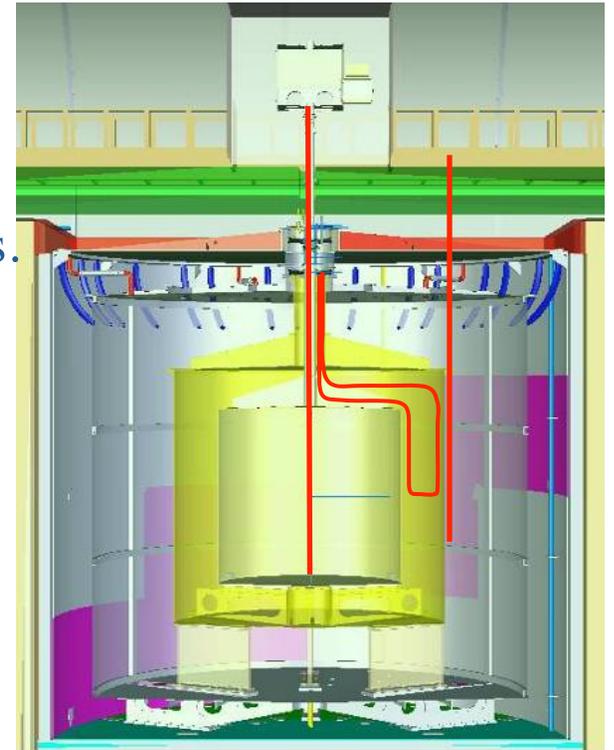
-Caveat: un-calibrated data shown.

-Stability of the Neutron capture on Hydrogen (2.2 MeV) after a muon: $\sim 10,000$ /day (right plot):



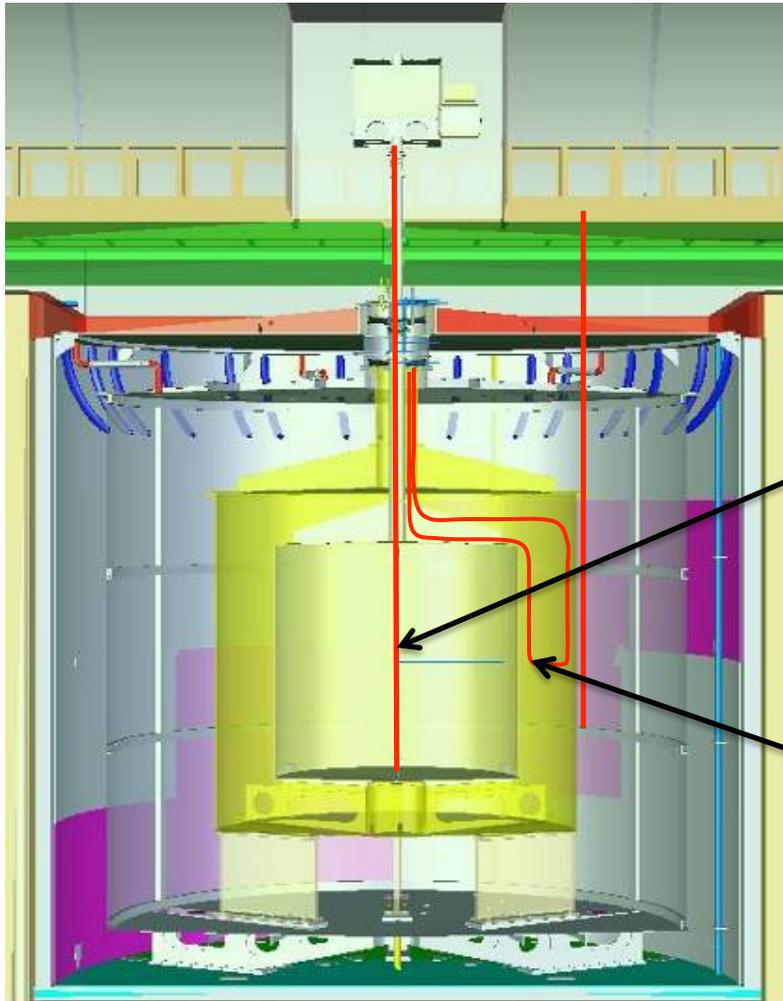
Calibration Systems

- Embedded LEDs inside inner detector and inner veto
→ routinely used to monitor detector stability & PMT gains.
 - Laser (UV and green)
 - Calibration source (γ , n, β) deployment devices:
 - Z-axis system (in target),
 - Guide tubes (in γ -catcher),
 - Articulated Arm. → near completion
- Radioactive sources deployed so far: Cs-137, Co-60, Ge-68, Cf-252.

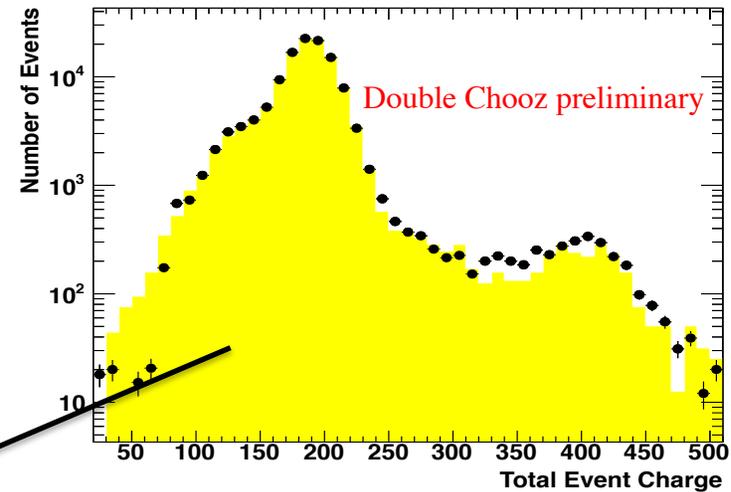


Detector Calibration

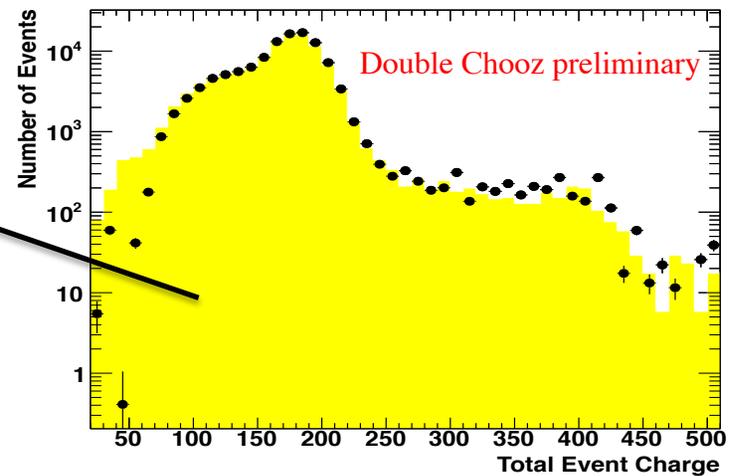
- ^{68}Ge at the Center of the Target and Gamma Catcher
- Positron source.
- The spectrum is well modeled.
- Verification of the energy threshold.



^{68}Ge Detector Center X=0mm, Y=0mm, Z=0mm



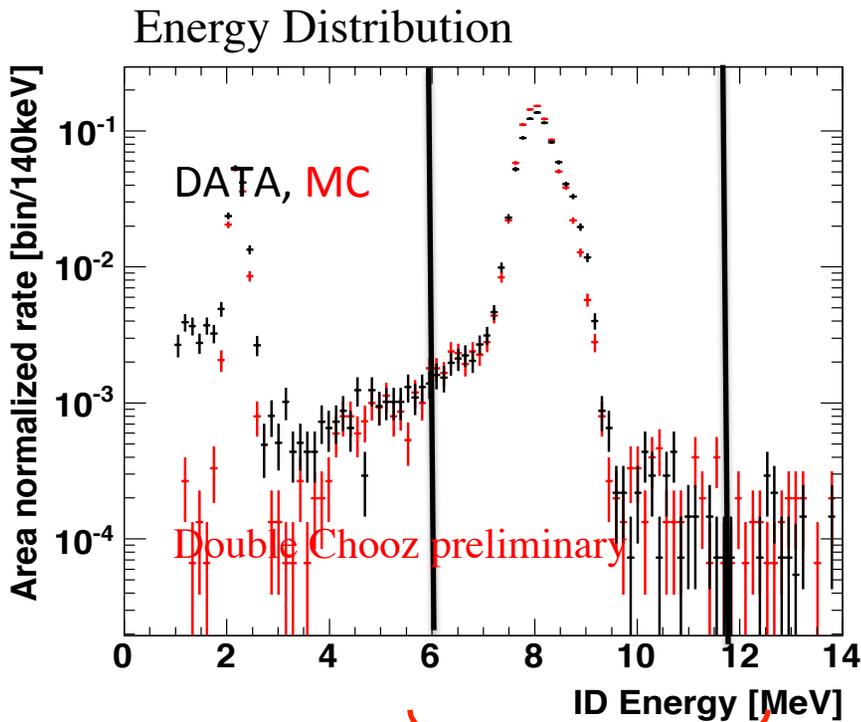
^{68}Ge Guide Tube X=0mm, Y=1433.9mm, Z=0mm



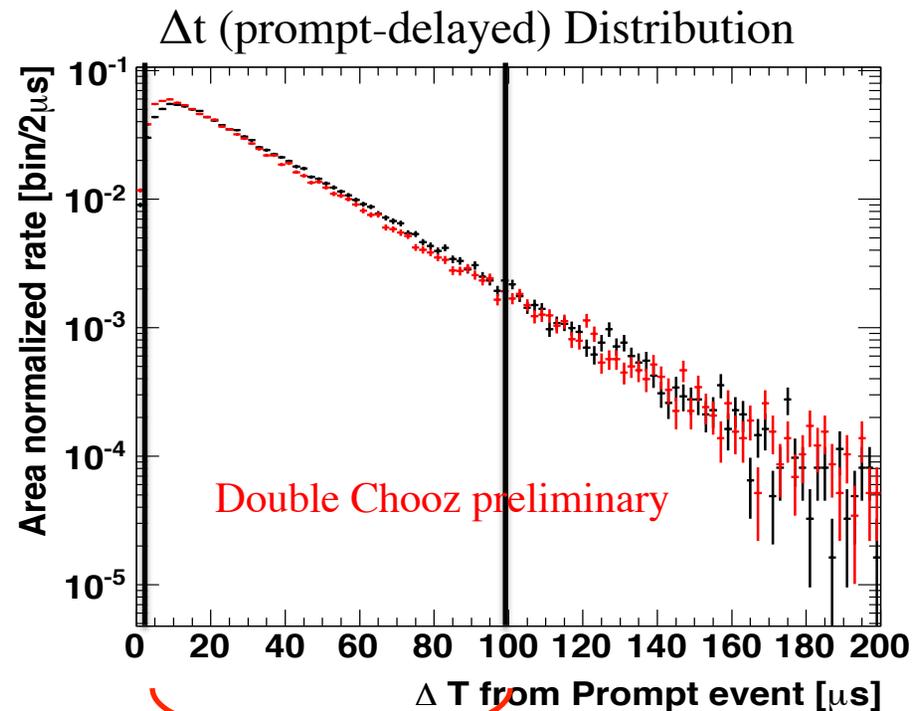
Detector Calibration

- ^{252}Cf at the detector center.

-Neutron source \rightarrow mimics neutrons from anti-neutrino interaction.



Region of interest
in neutrino candidate
search.



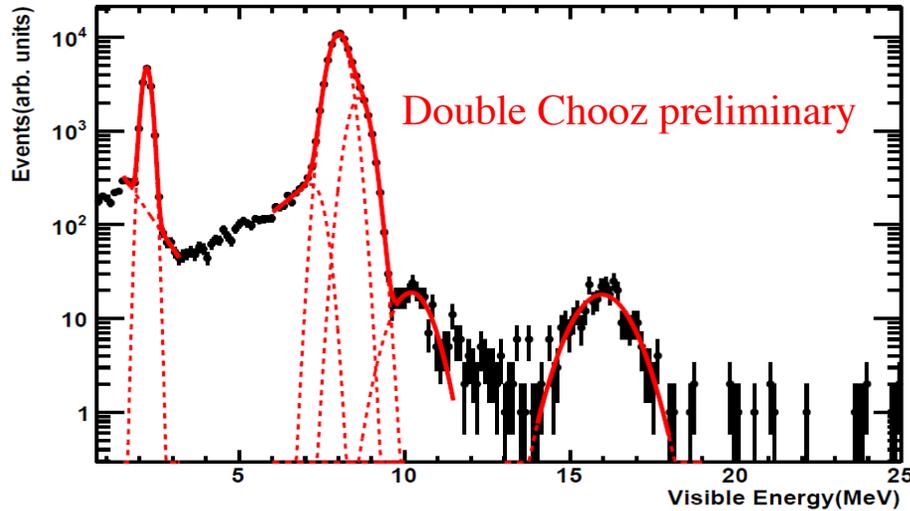
Region of interest in neutrino candidate
search.

(Data-MC)/Data relative difference:
 $\leq 0.5\%$ in the target.

Detector Calibration

- Gd-fraction fit.
- High intensity Cf data sample in the target central region (seven positions at Z-axis).

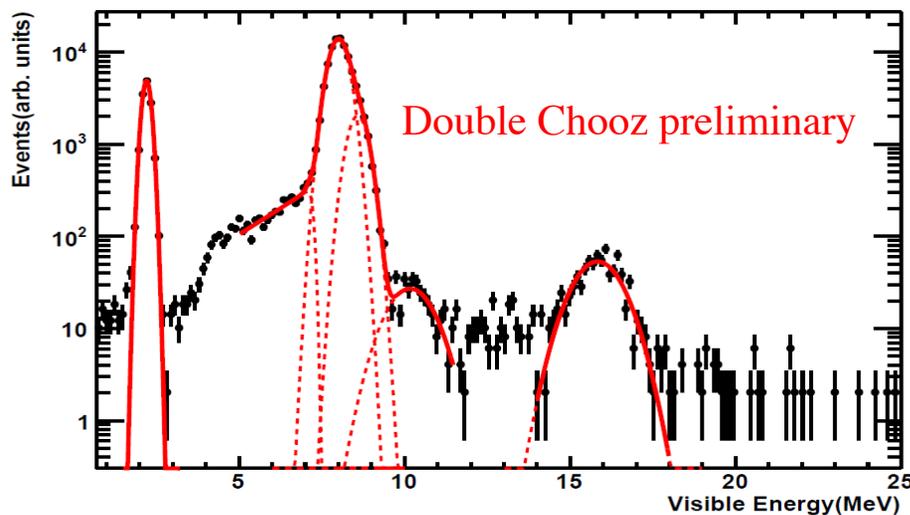
²⁵²Cf Data Delayed Signal



$Gd/(Gd+H) = 0.860 \pm 0.005$ [0.58% error].

2% correction between data and MC.

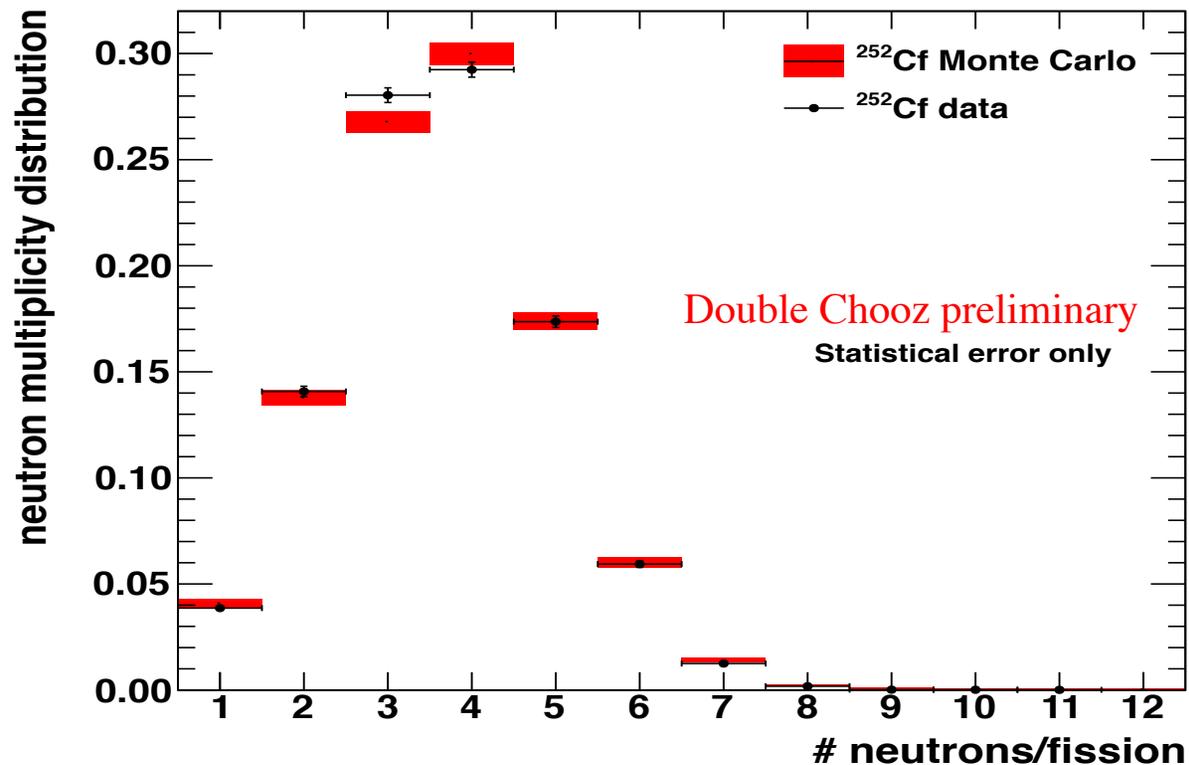
²⁵²Cf MC Delayed Signal



Detector Calibration

- ^{252}Cf multiplicity: well measured in literature.
- Important verification of neutron detection efficiency.

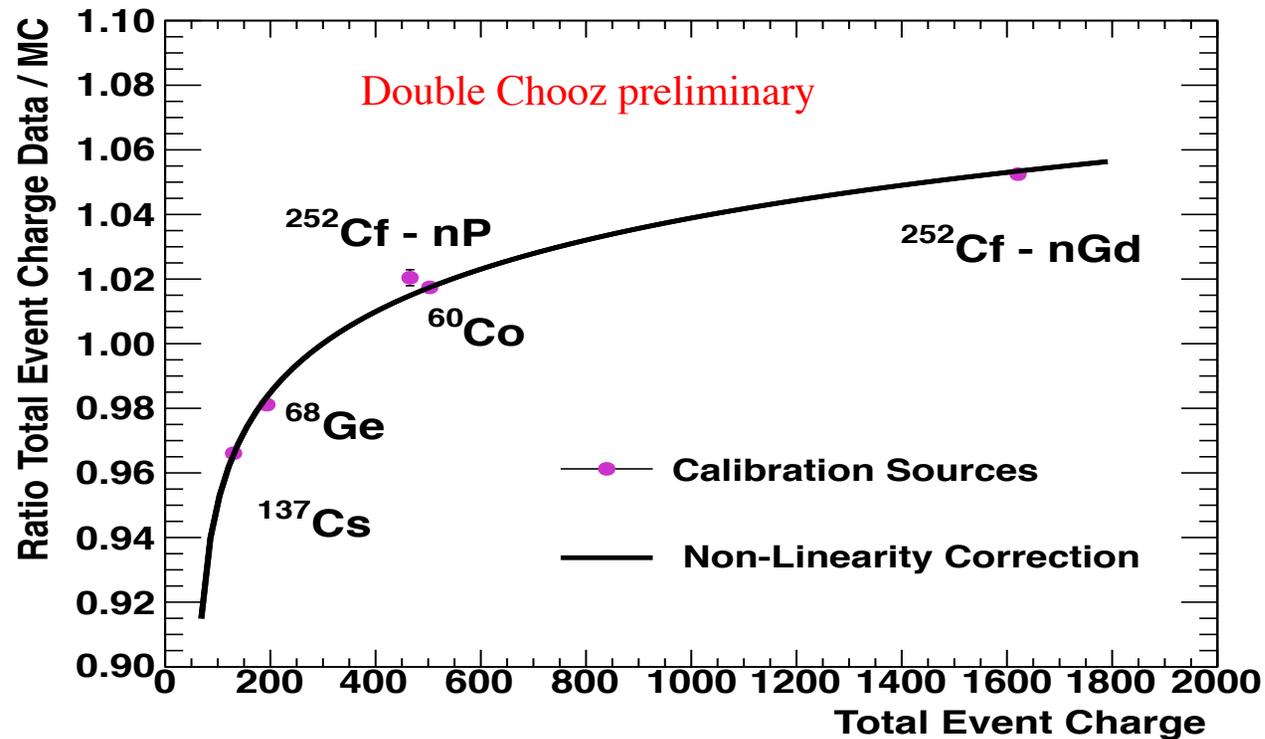
Multiplicity of total neutron capture (H+Gd)



- Using the first 8 neutron per fission only:
- Average neutron multiplicity **data**: 3.659 ± 0.008 (stat).
- Average neutron multiplicity **MC** : 3.677 ± 0.013 (stat).

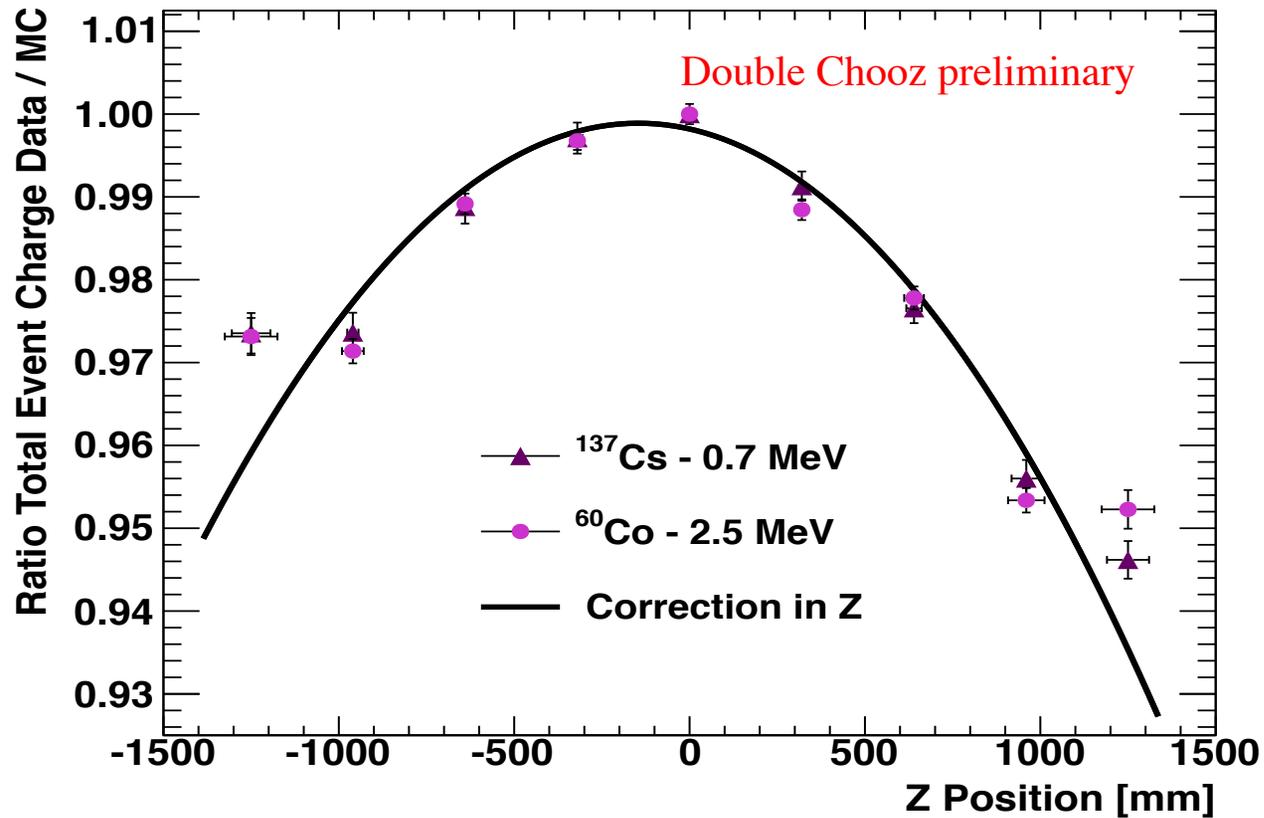
Detector Calibration

- Charge correction.
- Calibrate the non-linearity due to single photoelectron efficiency and electronics and charge-reconstruction effects.



Detector Calibration

- Position dependence correction.
- Residuals in the correction included in the detector covariance matrix.



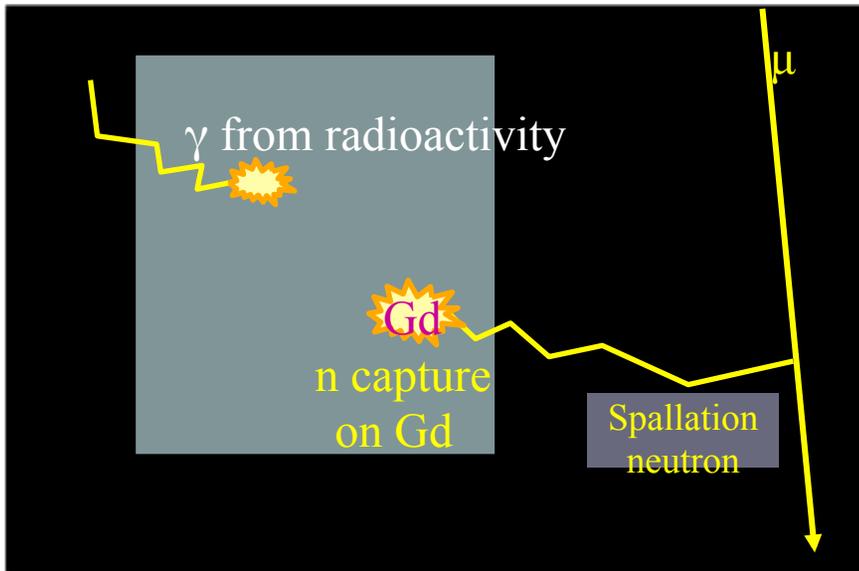
Neutrino Candidate Selection

- Remove all events 1msec after muon tagged by large inner-veto or inner-detector energy deposition.
- Remove light noise by charge/time requirement: $Q_{\max}/Q_{\text{tot}} < 0.09$ (0.06) & $\text{rms}(T_{\text{start}}) < 40$ ns.
- Prompt Event Requirement: $0 < E < 12$ MeV.
- Delayed Event Requirement: $6 < E < 12$ MeV.
- Time Coincidence Requirement prompt-delayed: $2 \mu\text{s} < \Delta t < 100 \mu\text{s}$.

Multiplicity Requirement:

- No triggers allowed in the $100 \mu\text{s}$ preceding the prompt E deposition.
- The time window from $2 \mu\text{s}$ to $100 \mu\text{s}$ following the prompt can contain only one valid trigger: the delayed candidate.
- No valid triggers allowed in the time window $100 \mu\text{s}$ through $400 \mu\text{s}$ after the prompt event.

Backgrounds

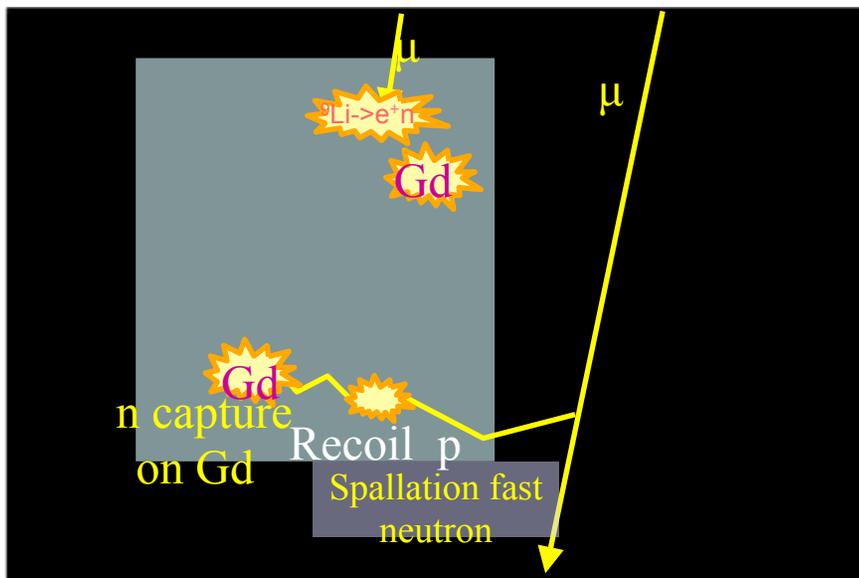


Classification:

-Accidental background

e^+ -like signal: radioactivity from materials, PMTs, surrounding rock (^{208}Tl).

neutron signal: n from cosmic μ spallation, thermalized in detector and captured on Gd.



-Correlated background

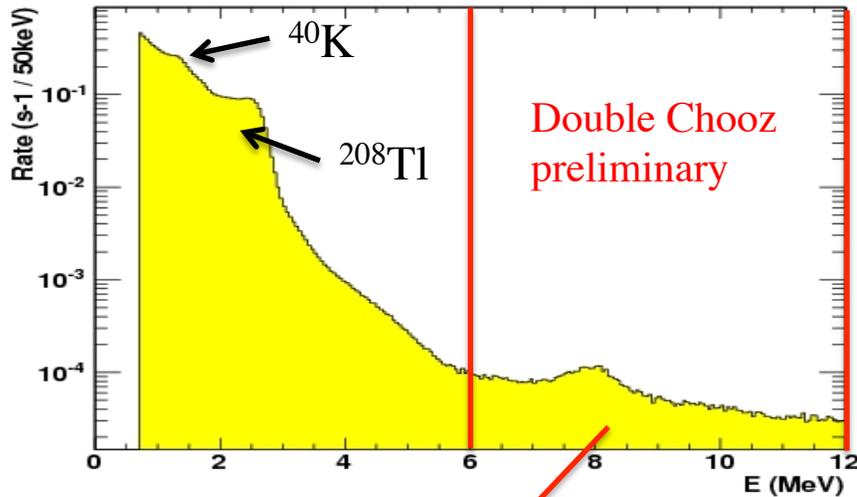
Fast neutrons (by cosmic μ) gives recoil protons (low energy) and are captured on Gd.

Stopping-muons followed by muon-decay
Michel electron/positron

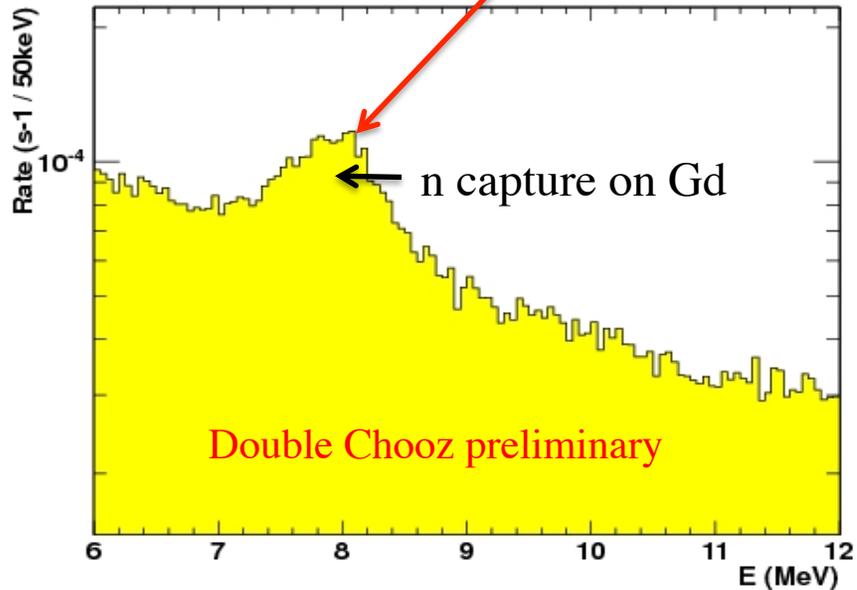
Long-lived (^9Li , ^8He) $\beta+n$ -decaying isotopes induced by μ .

Backgrounds

Single (accidental) Background (no selection applied):

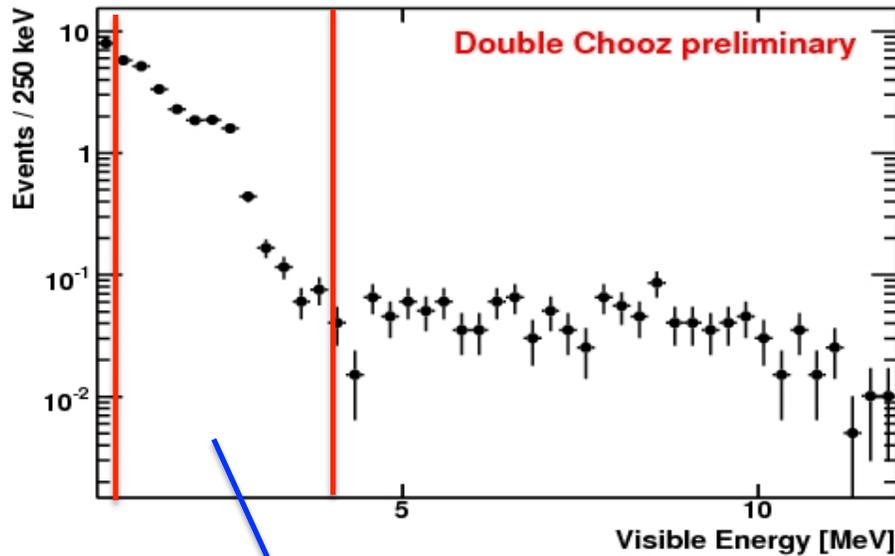


- Energy spectrum of single events in [0.7,12] MeV region.
- Natural Radioactivity



- Energy spectrum of single events in [6,12] MeV region.
- Spallation neutrons

Backgrounds: Accidental



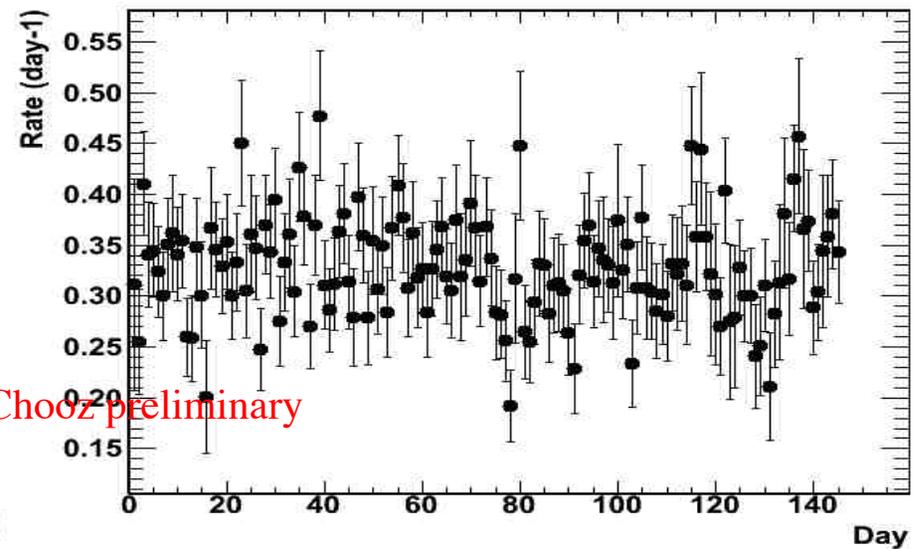
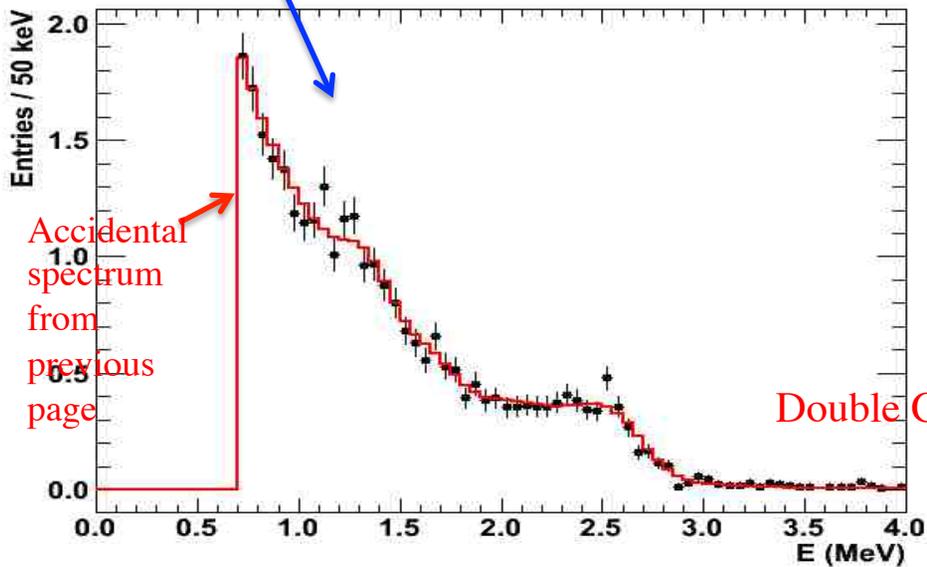
Analysis method:

-Neutrino search with delayed event in off-time window [1,100] ms.

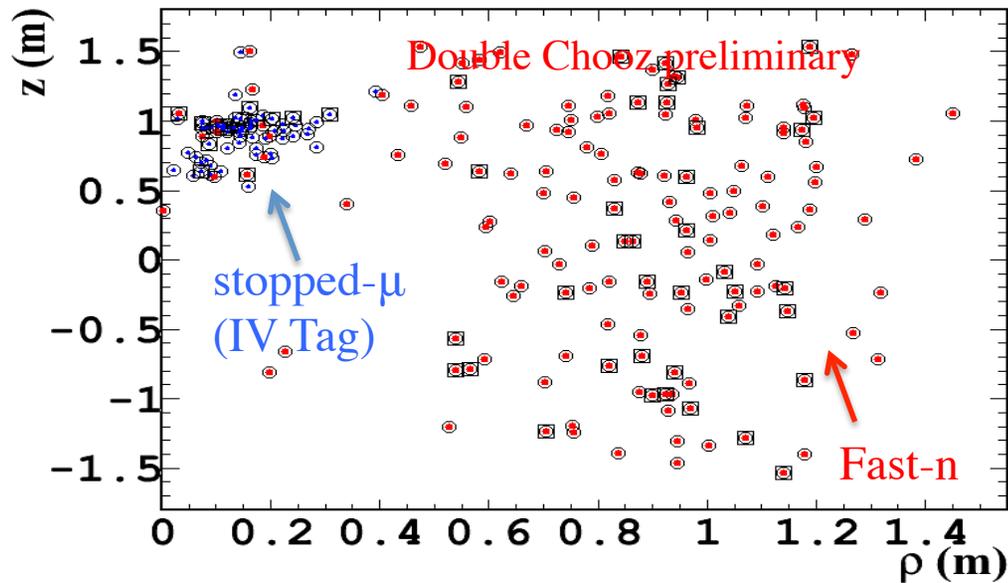
Rate = $(0.332 \pm 0.004)/\text{day}$.

-Spectrum consistent with “single” backgrounds.

-Stable in time



Backgrounds: Fast Neutrons

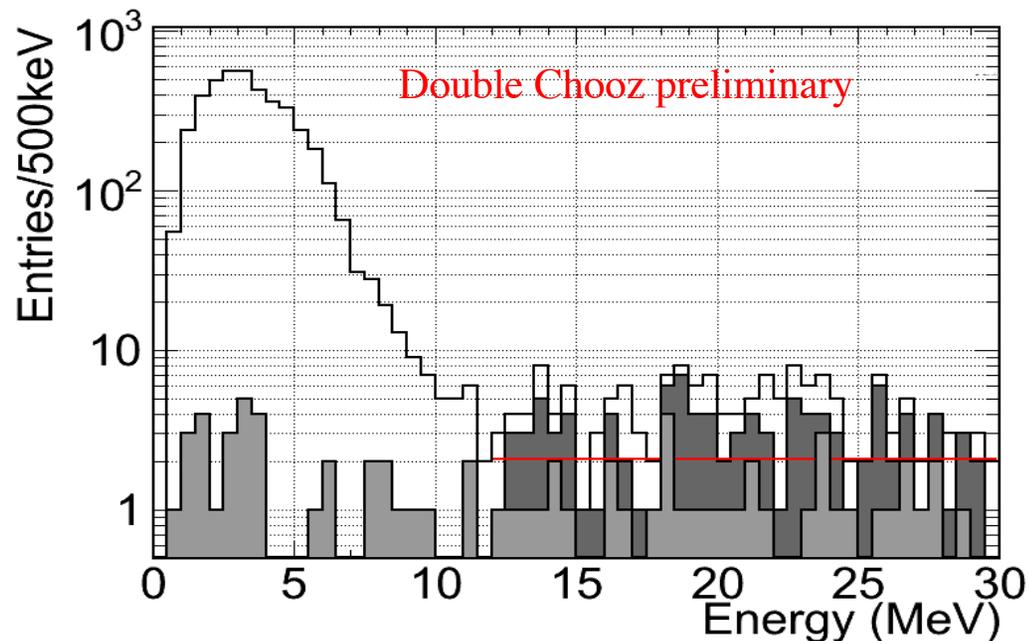


Analysis method:
-Prompt energy range extended to 30 MeV.

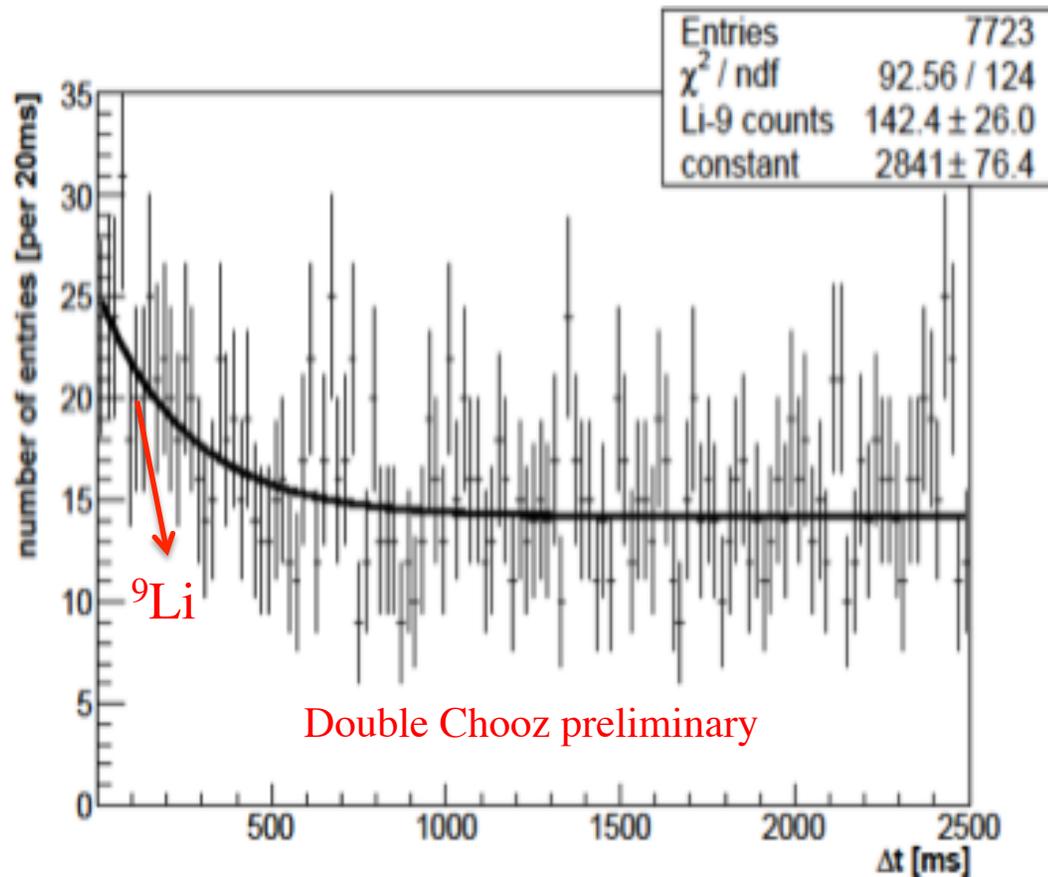
Two event populations:
-Fast neutrons
-Stopping muons

-Extrapolation from high-E to low-E:
Rate = (0.7 ± 0.5) /day.

Oscillation (θ_{13}) fit:
-Use flat energy spectrum.
-Deviations taken as spectral uncertainties.



Backgrounds: ${}^9\text{Li}$



Analysis method:

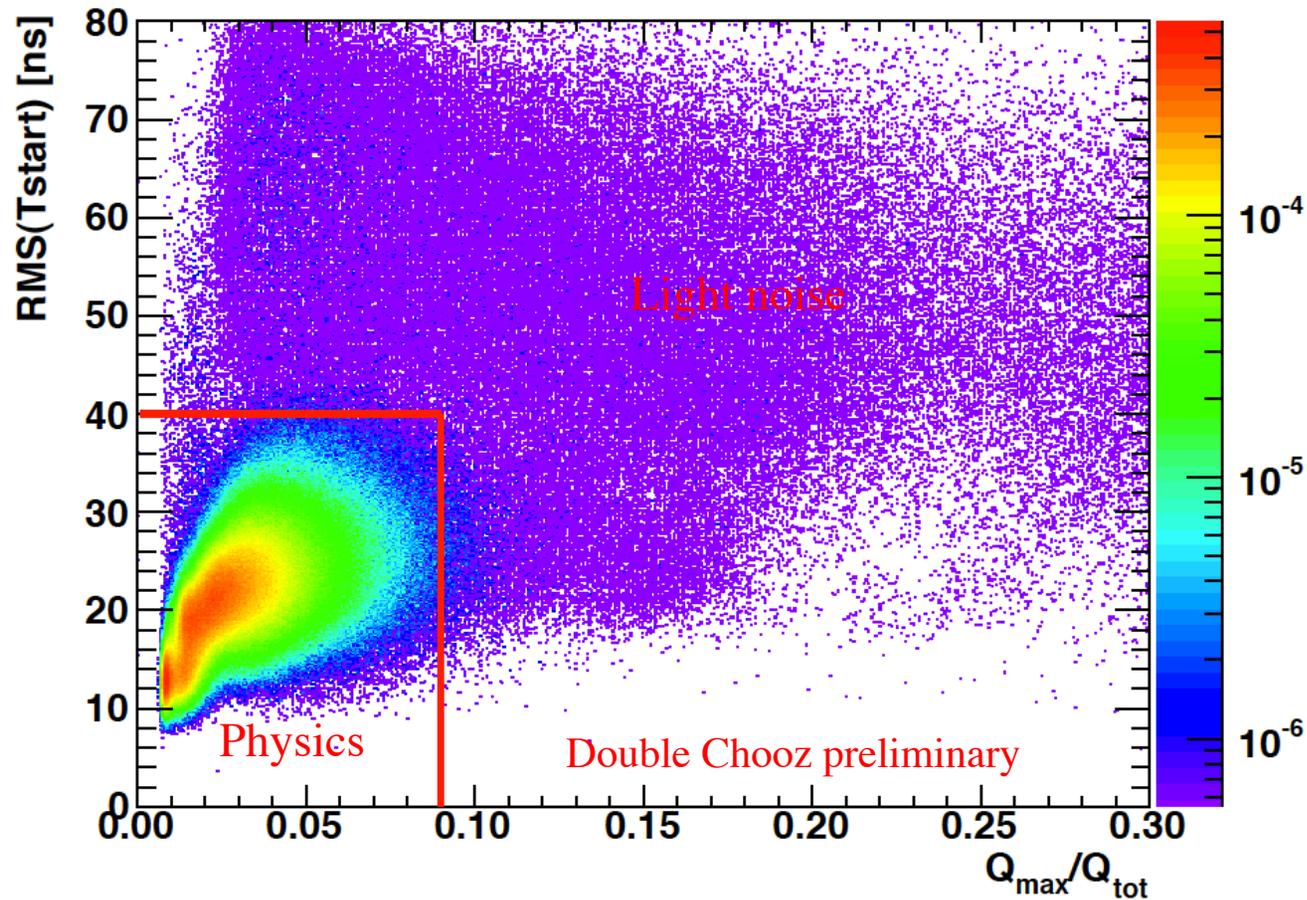
- Search for a triple delayed coincidence between showering muon and neutrino-like coincidence
- Δt between showering muon and prompt event is given by the ${}^9\text{Li}$ -like life time (257ms).

Rate = (2.3 ± 1.2) /day.

- Spectrum from nuclear database.

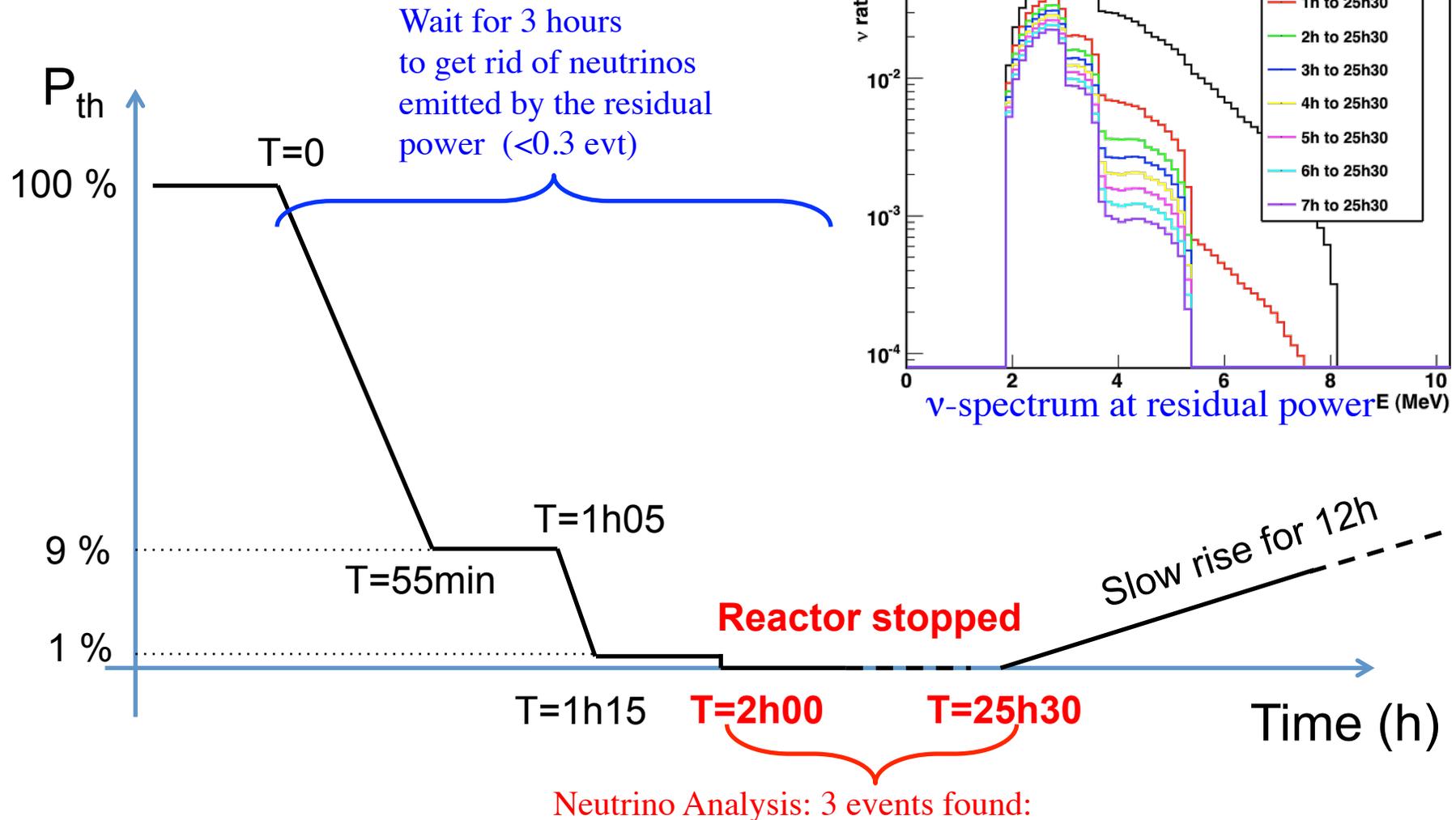
Backgrounds: An unexpected background (Light Noise)

- Instrumental light emission from PMTs was observed: PMT sees its own light.
- The rate has the same order of magnitude as the single accidental rate, but very different charge/time behavior.
- Characterized by
 - Q_{\max}/Q_{tot} : how evenly charge is spread among PMTs, and
 - $\text{rms}(T_{\text{start}})$: spread in photon arrival times
- Effective selection criteria developed to remove it.



Background Cross-check with Reactor OFF Period

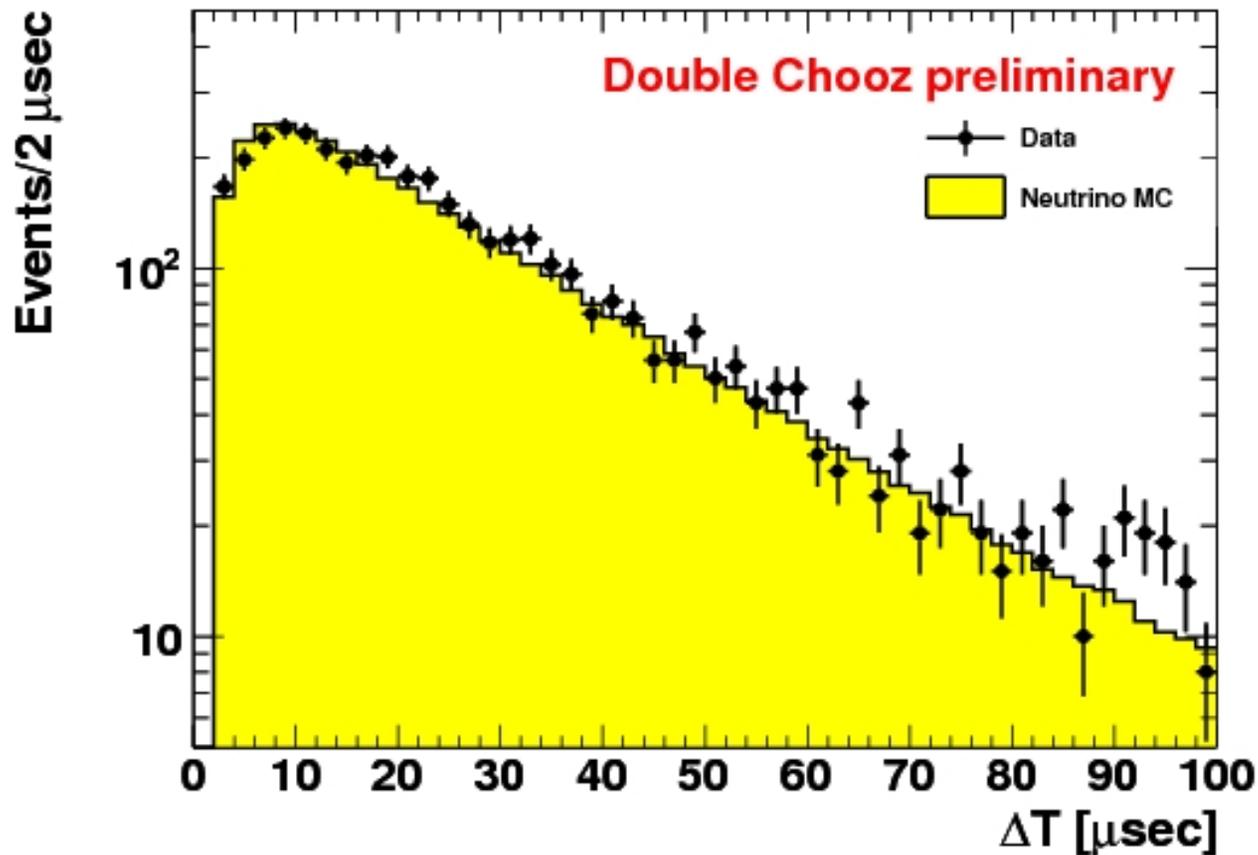
- One reactor OFF for 2 months (re-fuelling).
- Second reactor OFF for one day (perform tests).
- Data analysis finds 3 events with $E < 30 \text{ MeV}$:



- Two possible Li/He candidates, one consistent with stopping-muon candidate (under chimney).

Neutrino Candidate Selection

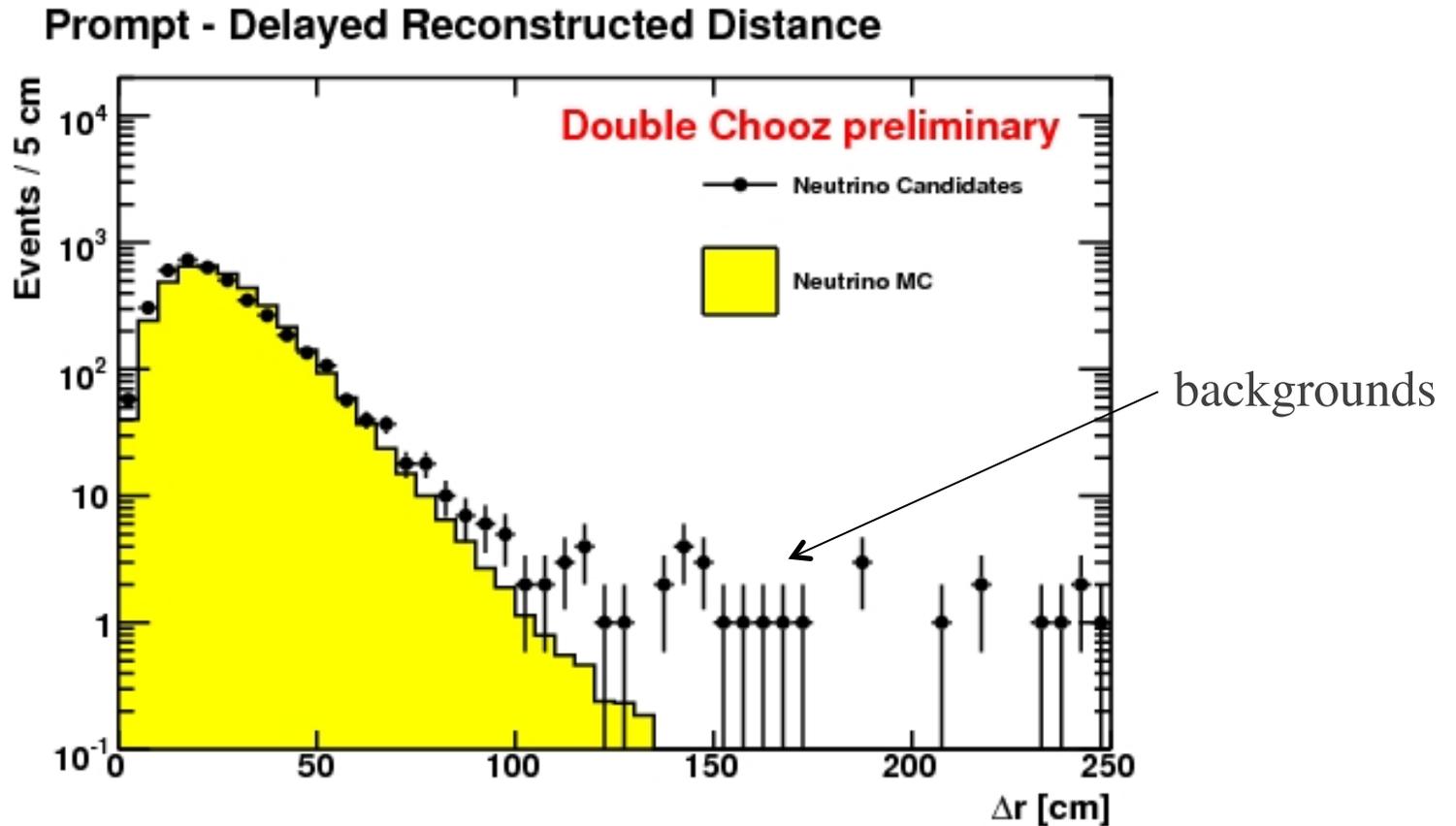
- keV neutrons thermalize within a few μs .
- Then neutrons get captured on Gd with $\tau = 27\mu\text{s}$.
- Good agreement with the MC expectation.



-The efficiency within $[2,100]$ μs is $0.965 \pm 0.5\%$.

Neutrino Candidate Selection

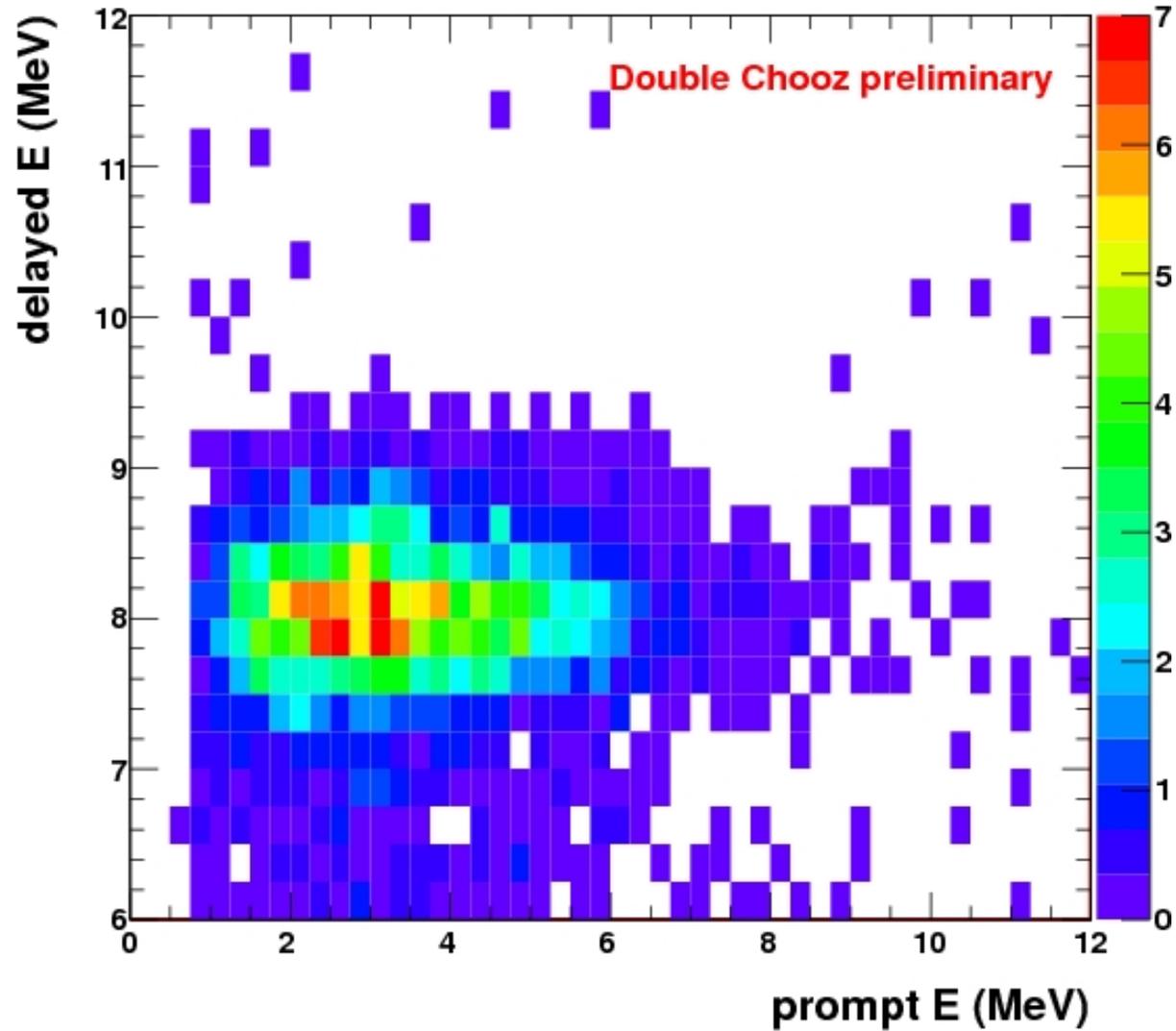
- Low level of accidental background.
- No Need for ΔR Cut (as designed in the proposal).



Neutrino Candidate Selection

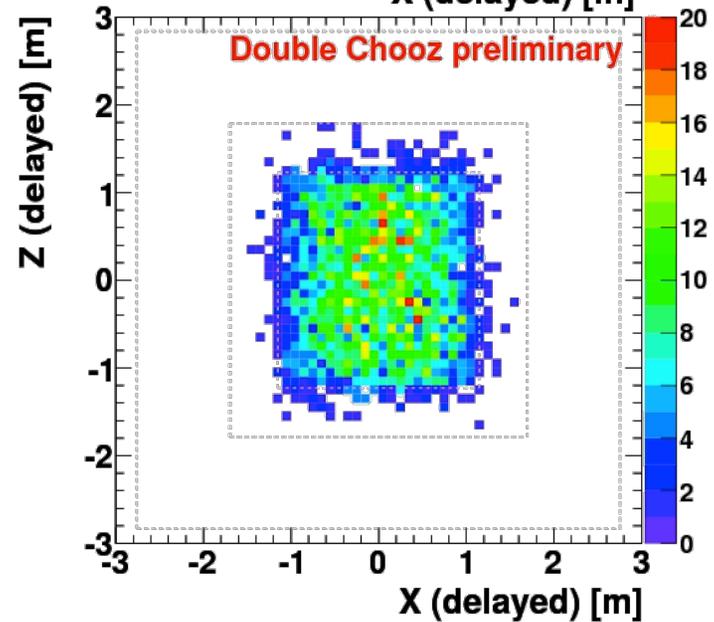
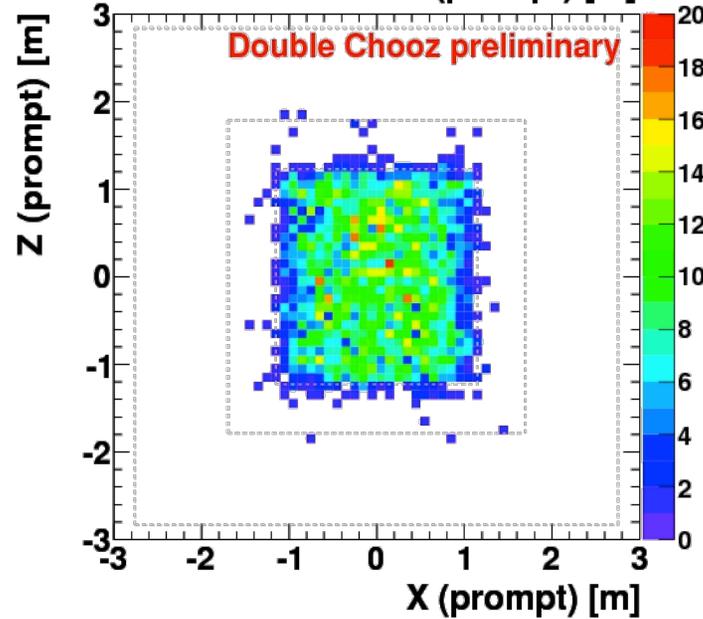
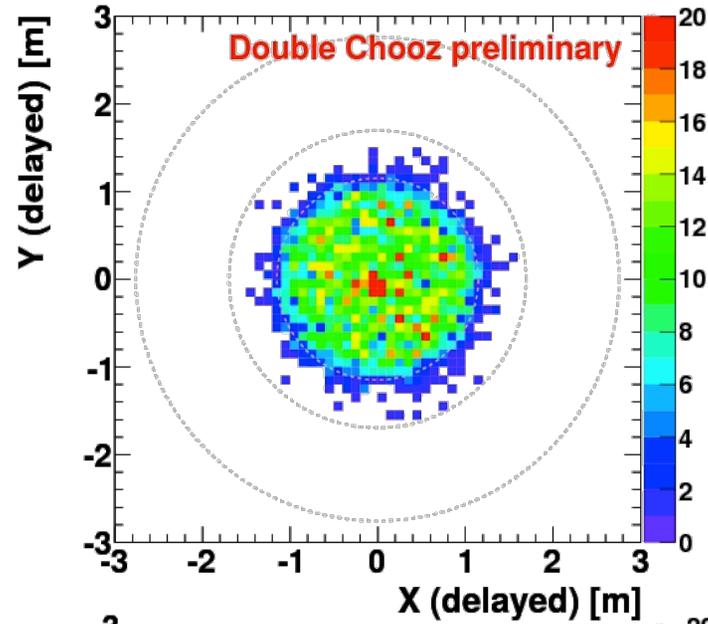
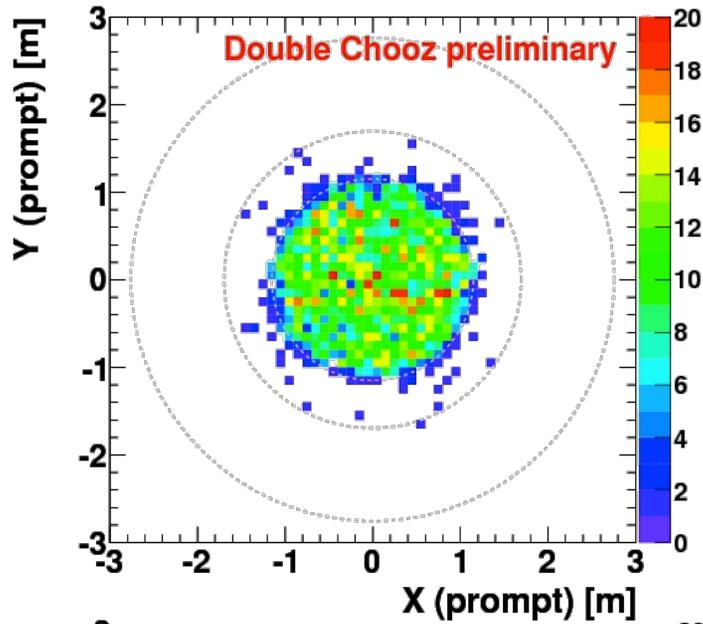
$-E_{\text{prompt}}$ VS E_{delayed}

E_{prompt} VS E_{delayed}



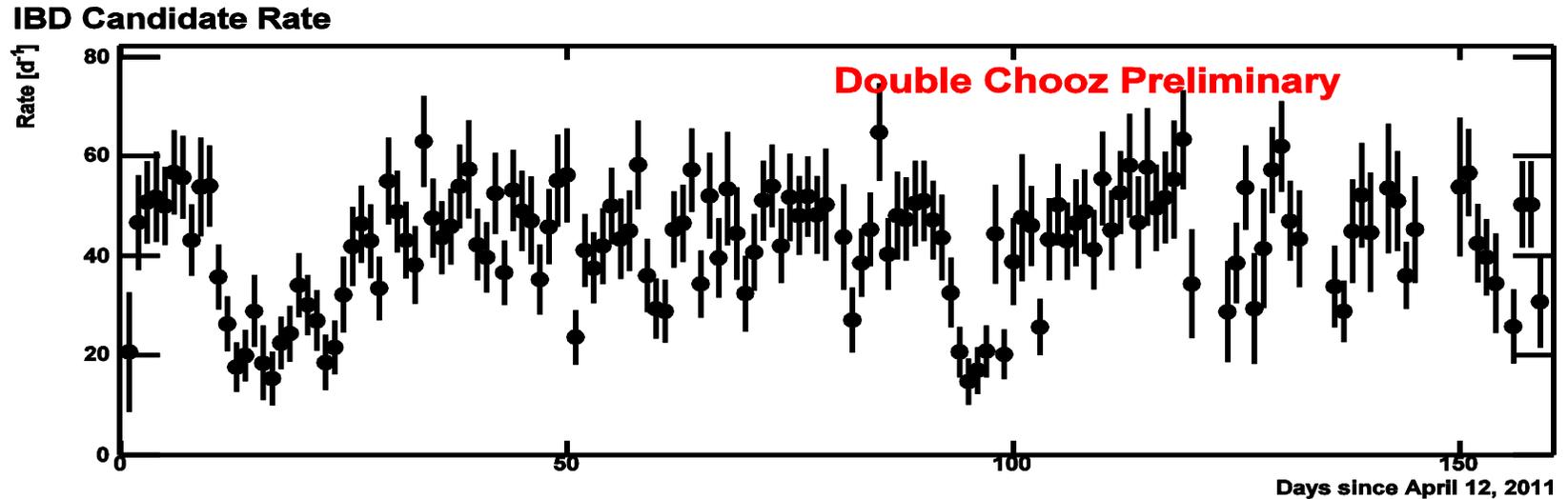
Neutrino Candidate Selection

-Prompt & Delayed Vertex Reconstruction (cross-check only).



Neutrino Candidate Selection

-Rate of Anti-neutrino candidates as function of time



Event Type	N_{Events}	Rate/Day	σ/Day
Neutrino Candidates	4121	42.6	0.7
Expected Accidentals	31.60	0.32	0.06
Expected ⁹ Li	227.3	2.3	1.2
Expected Fast-n	69.2	0.7	0.5

-Need predicted spectrum with no-oscillation to perform oscillation search.

Table of Systematics

Source	Uncertainty
Target Free H	+/- 0.3 %
Trigger Efficiency	+/- 0.5 %

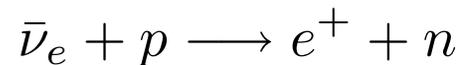
Source	Efficiency	Uncertainty	}	78 %
Prompt Event	99.9 %	+/- 0		
Delayed Event	86.0 %	+/- 0.6 %		
Δt Cut	96.5 %	+/- 0.5 %		
ΔE Cut	94.5 %	+/- 0.6 %		

Source	MC Live Time Correction	Uncertainty	}	92.4%
Muon Deadtime	0.955	+/- 0		
Multiplicity	0.995	+/- 0		
Gd Fraction	0.98	+/- 0.6 %		
Spill in/out	0.993	+/- 0.4 %		

Anti-neutrino Spectrum Prediction

- "Reactor Anomaly" and DC analysis with the far Detector only strategy:
use the experimental cross section per fission of Bugey-4 (apply burn-up correction).

- The Bugey-4 measurement is used as an anchor point for the prediction of the detected spectrum, renormalizing possible error in the converted reference spectra or possible existence of an oscillation toward a sterile neutrino at very short baseline.



$$n_\nu = \frac{1}{4\pi R^2} \frac{P_{\text{th}}}{\langle E_f \rangle} N_p \varepsilon \sigma_f \longrightarrow \sigma_f^{\text{meas.}} = \frac{4\pi R^2 n_\nu^{\text{meas.}} \langle E_f \rangle}{N_p \varepsilon P_{\text{th}}}$$

Measured in Bugey4 experiment.

Anti-neutrino Spectrum Prediction

$$N_{\nu}^{\text{exp}}(E, t) = \frac{N_p}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

- Mean energy per fission:

$$\langle E_k \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

$$k = {}^{235}\text{U}, {}^{238}\text{U}, {}^{239}\text{Pu}, {}^{241}\text{Pu}$$

α_k : fractional fission rate

- Mean cross-section per fission:

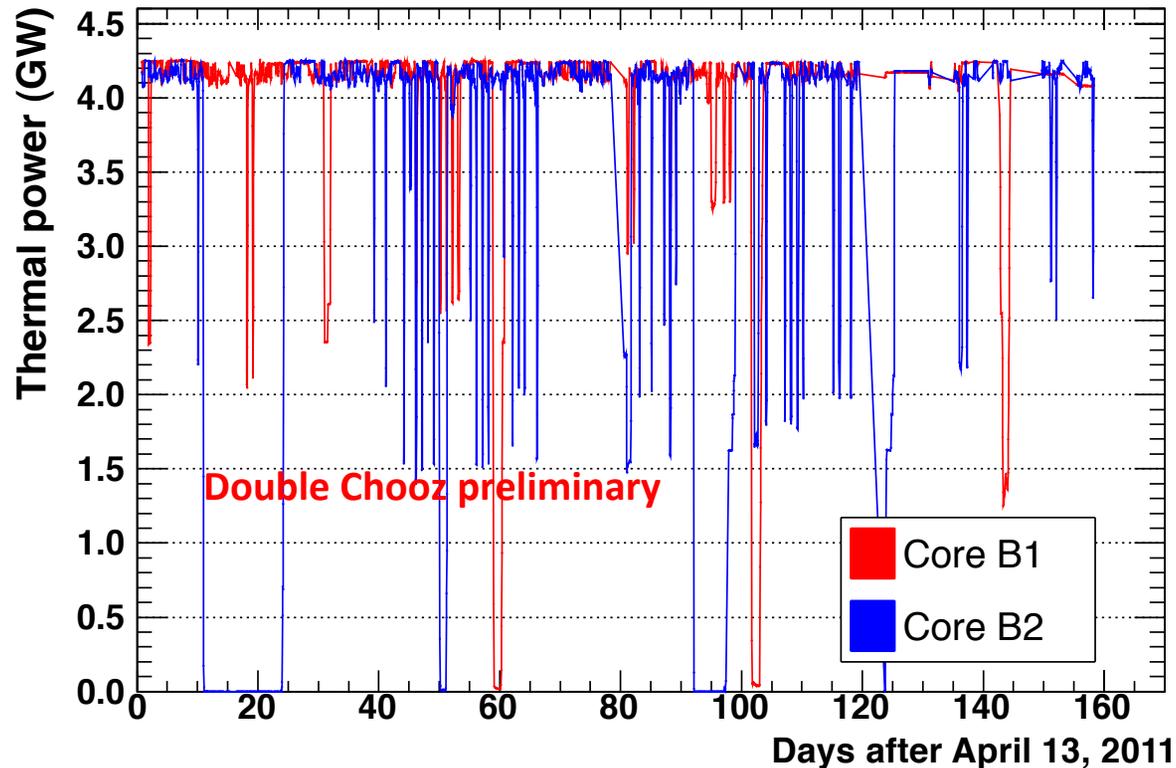
$$\langle \sigma_f \rangle_k = \int_0^{\infty} dE S_k(E) \sigma_{IBD}(E)$$

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{\text{Bugey}} + \sum_k \left(\alpha_k^{\text{DC}}(t) - \alpha_k^{\text{Bugey}}(t) \right) \langle \sigma_f \rangle_k$$

Bugey4 anchor point -> our current “near” detector

Anti-neutrino Spectrum Prediction

-Thermal Power Measurement:



-Precise weekly measurements by enthalpic balance in the secondary loop (at steam generators).

-Monitoring every minute, based on temperature in primary loop.

Anti-neutrino Spectrum Prediction

-Reactor Evolution Code:

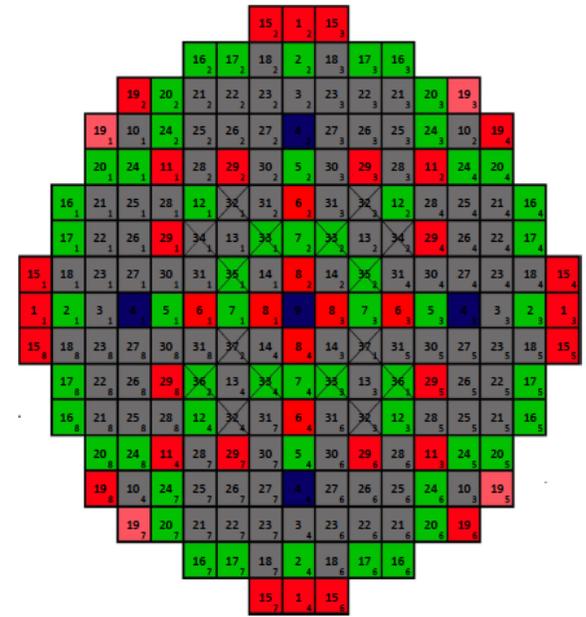
Development of full core simulation with MURE Code (Subatech), cross-checked with DRAGON code, and EDF calculation.

-Use list of EDF inputs (initial fuel loading, geometry, power history, boron concentration, T, ...)

-Complete error budget based on uncertainty on reactor parameters, code comparison, nuclear database inputs.

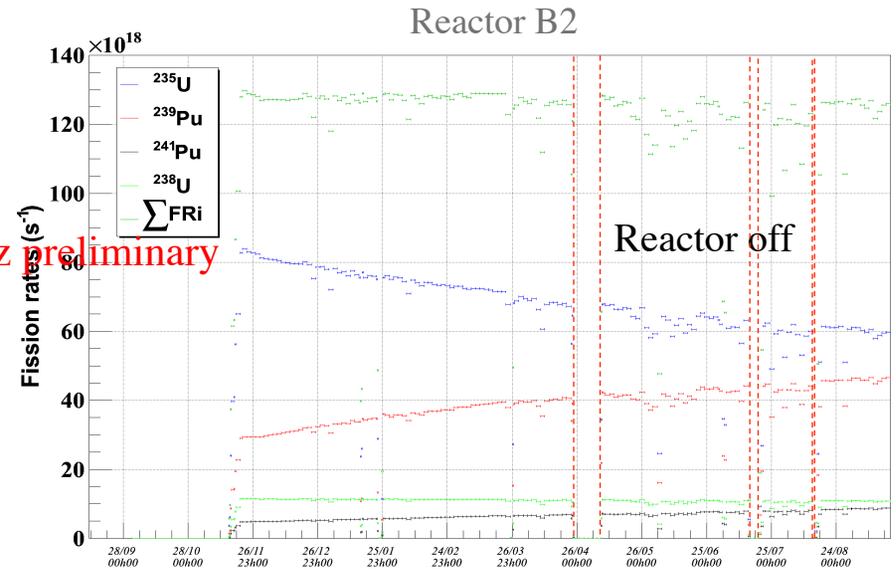
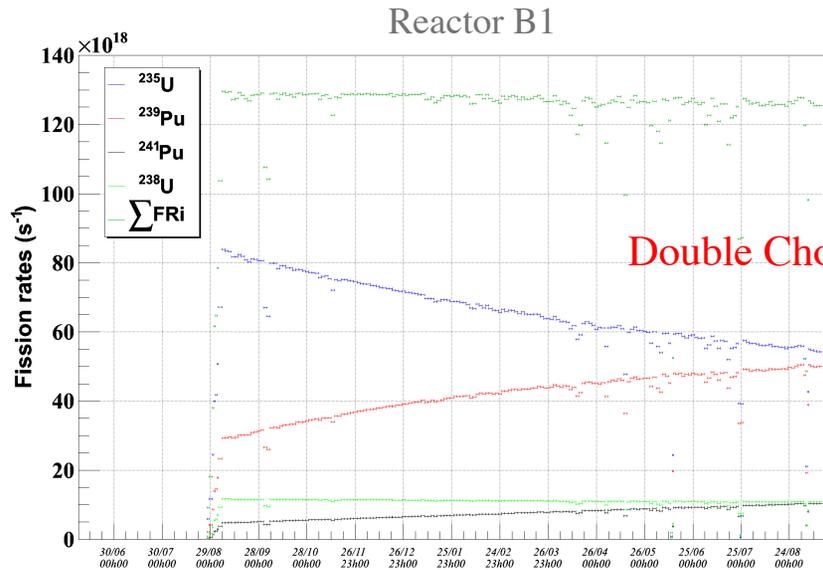
-Code validated with set of benchmarks (comparison of code prediction to data with samples from reactor core)

see C.Jones et al., “Reactor Simulation for Antineutrino Experiments using DRAGON and MURE.”, arXiv:1110.6249 [hep-ex].

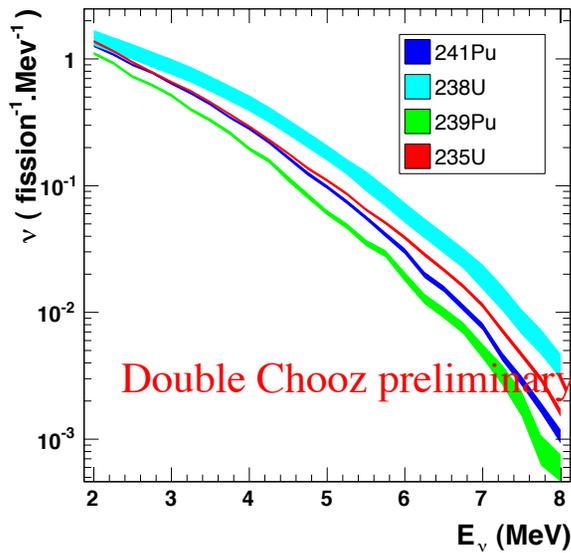


Anti-neutrino Spectrum Prediction

-Calculated Fission Rates:



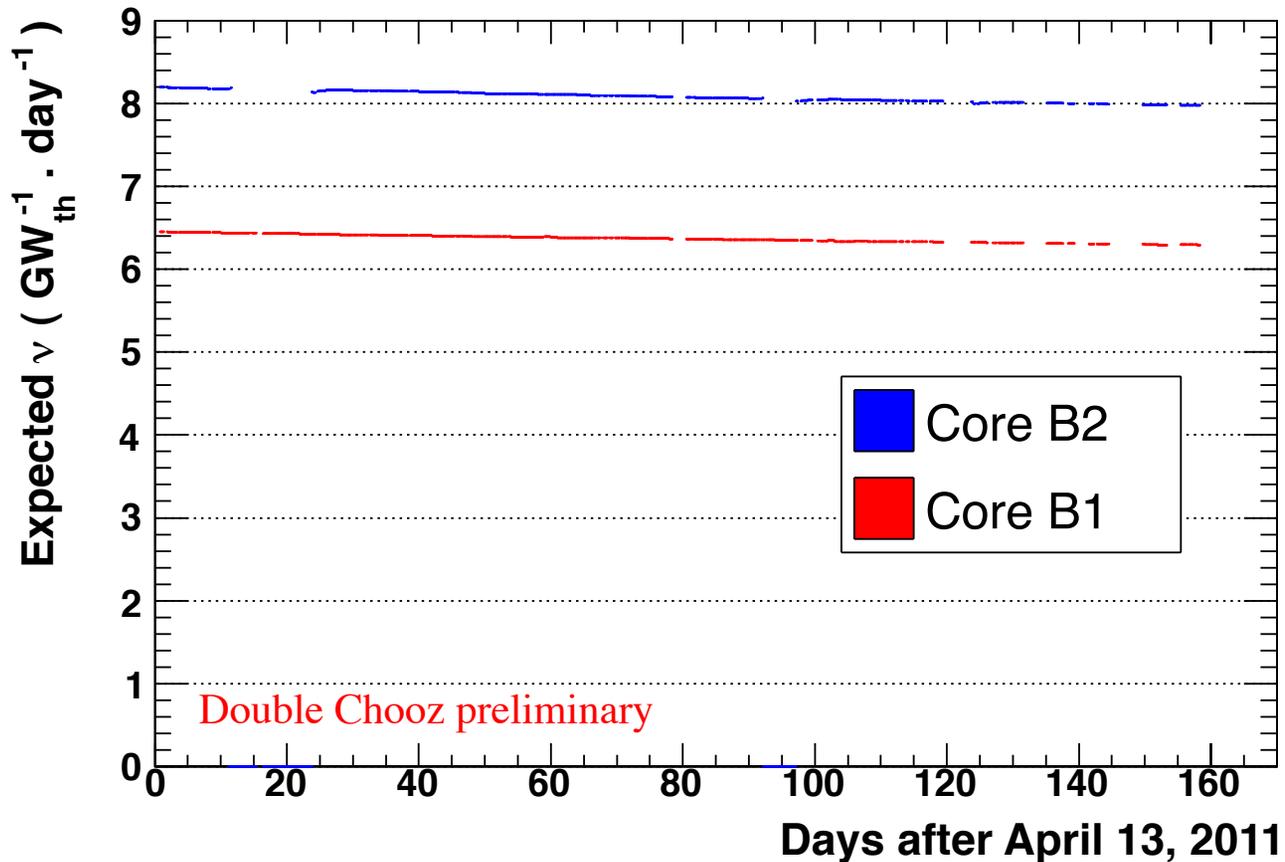
-Neutrino Spectrum (per fission):



-Recent re-evaluations of fissile isotopes by
-Th. A. Mueller et al, Phys.Rev. C83(2011) 054615.
-P. Huber, Phys.Rev. C84 (2011) 024617.

Anti-neutrino Spectrum Prediction

-Predicted emitted Anti-neutrino rate



-2.5% reduction of neutrino rate during data taking due to accumulation of ^{239}Pu in the core

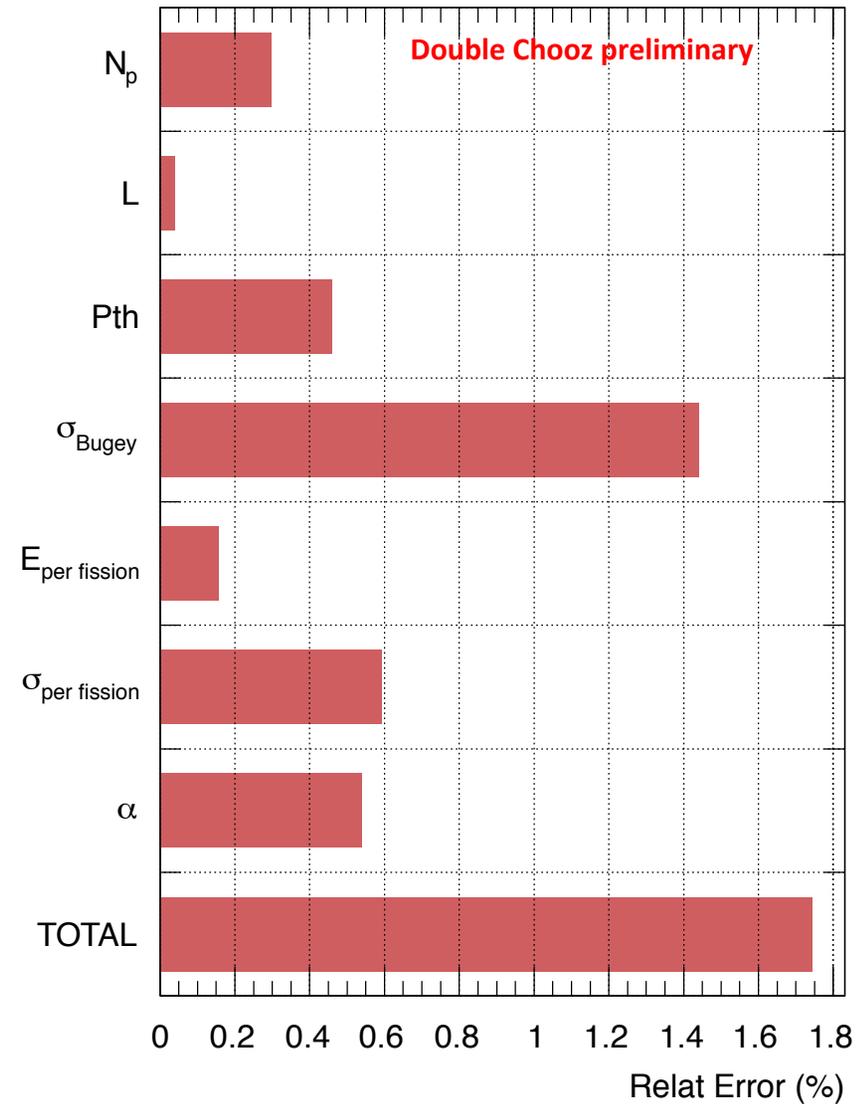
Anti-neutrino Spectrum Prediction

-Error on Predicted Anti-neutrino Spectrum:

-Anchor point of Bugey4 measurement suppresses sensitivity to reference spectra ($\sigma_{\text{per fission}}$)

-Accurate reactor simulation with MURE keep contribution of the uncertainty on fission rates low.

-1.7% total error (2.7% if no Bugey4 anchor).



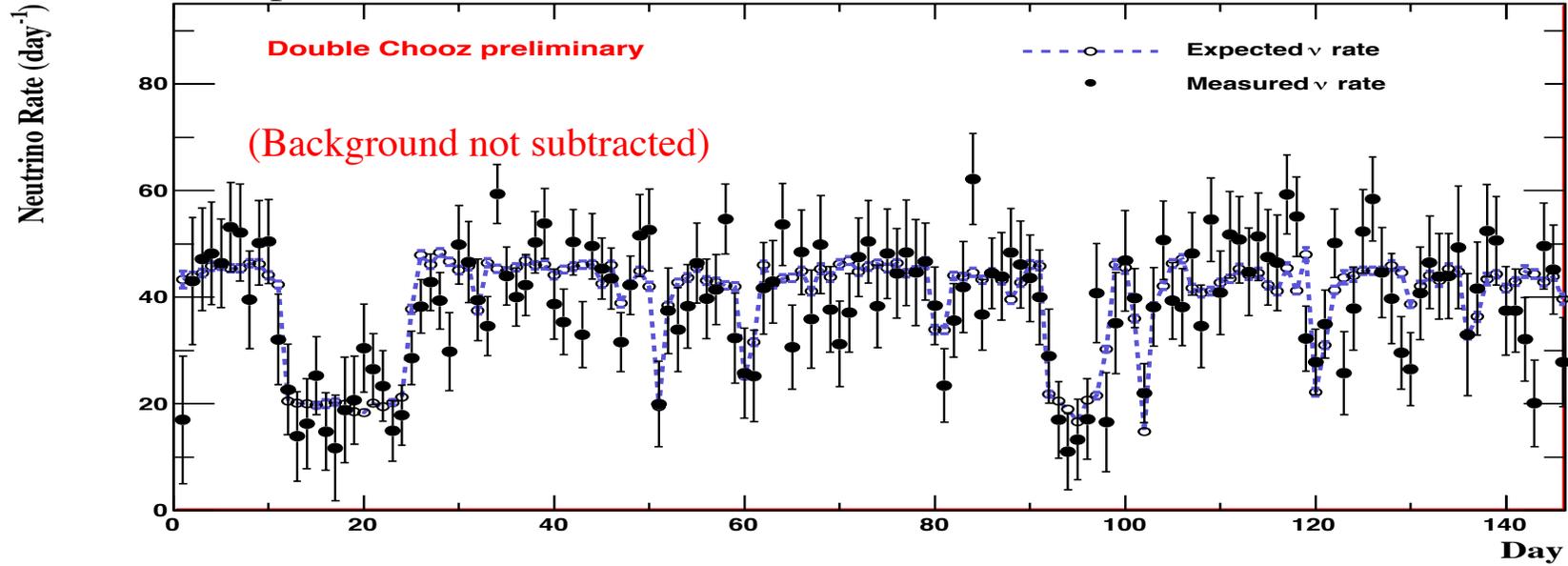
Anti-neutrino Spectrum Prediction

-Predicted number of neutrinos:

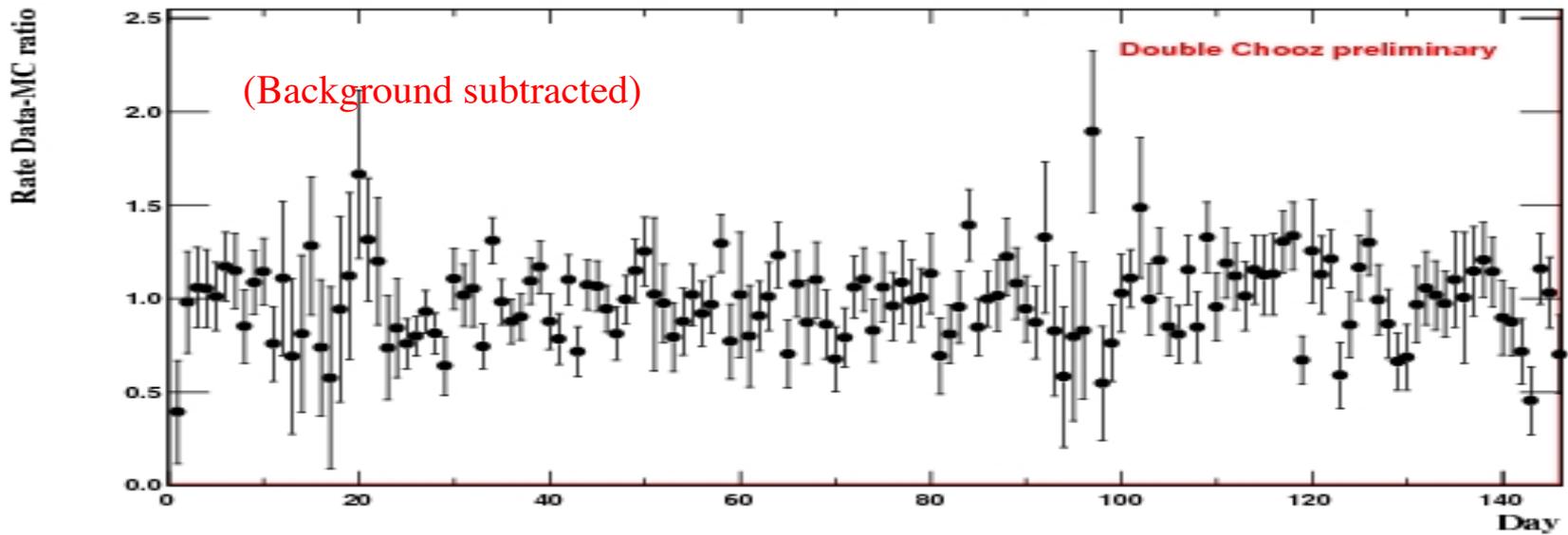
$$\begin{array}{rcl} \text{Reactor B1} & & 2583.5 \\ & + & \\ \text{Reactor B2} & & 2751.2 \\ & = & \\ \text{Total} & & 5334.7 \pm 93 (1.74\%) \end{array}$$

Back to Oscillation Search

-Measured vs Expected



Neutrino Rate Data-MC ratio



Back of Envelope Calculation

-Data (Neutrino Candidates) : 4121 (+ bkg = 328).

-MC (Expected Signal) : 5339 (before efficiency correction)

- $N_{\text{neutrinos}}$ (observed) = $(4121 - 328) = 3793$.

- $N_{\text{neutrinos}}$ (predicted) = $5339 \times 0.757 = 4041$.

-Use this:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \underbrace{\sin^2(1.27\Delta m_{31}^2 L / E_\nu)}_{0.54}$$

$$\sin^2 2\theta_{13} = \frac{\left(1 - \frac{N_{\text{observed}}}{N_{\text{predicted}}}\right)}{1 - 0.54} \approx 0.13$$

-There is a better way to do this.

Oscillation Fit

$$\begin{aligned}
 \chi^2 = & \left(N_i - \left(\sum_R^{\text{Reactors}} N_i^{\nu,R} + \sum_b N_i^b(P_b) \right) \right) \times \left(M_{ij}^{\text{signal}} + M_{ij}^{\text{detector}} + M_{ij}^{\text{stat}} + \sum_b^{\text{bkgnds.}} M_{ij}^b \right)^{-1} \\
 & \times \left(N_j - \left(\sum_R^{\text{Reactors}} N_j^{\nu,R} + \sum_b N_j^b(P_b) \right) \right)^T \\
 & + \sum_R^{\text{Reactors}} \frac{(P_R)^2}{\sigma_R^2} \\
 & + \sum_b^{\text{bkgnds.}} \frac{(P_b)^2}{\sigma_b^2}
 \end{aligned}$$

N_i - Number of observed ν events in prompt energy bin i

$N_i^{\nu R}$ - Number of observed events in prompt energy bin i from reactor R

N_i^b - background events in bin i from background b

M_{ij}^{signal} - signal covariance matrix

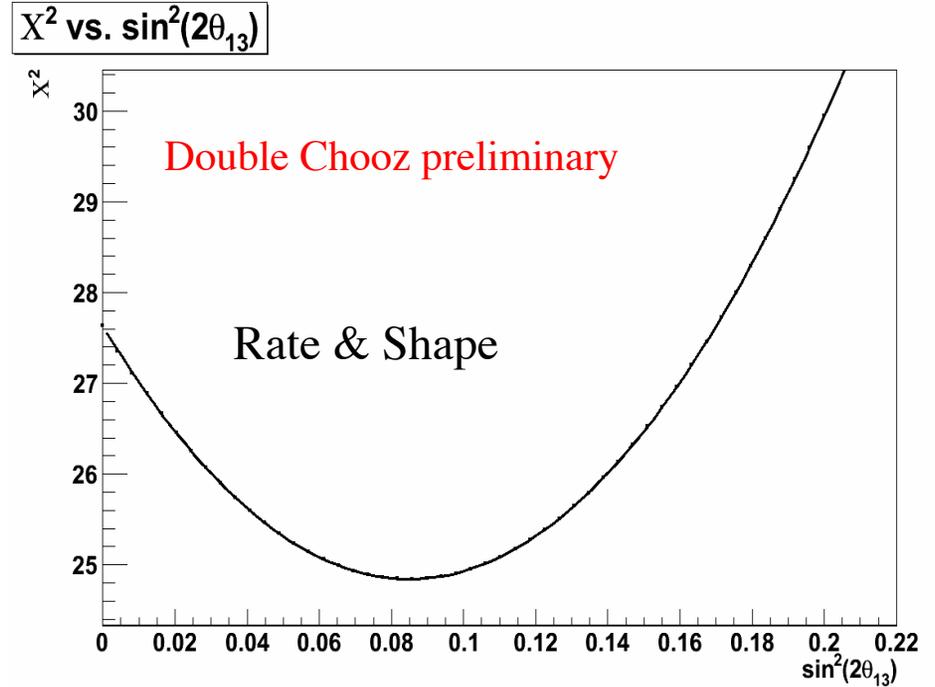
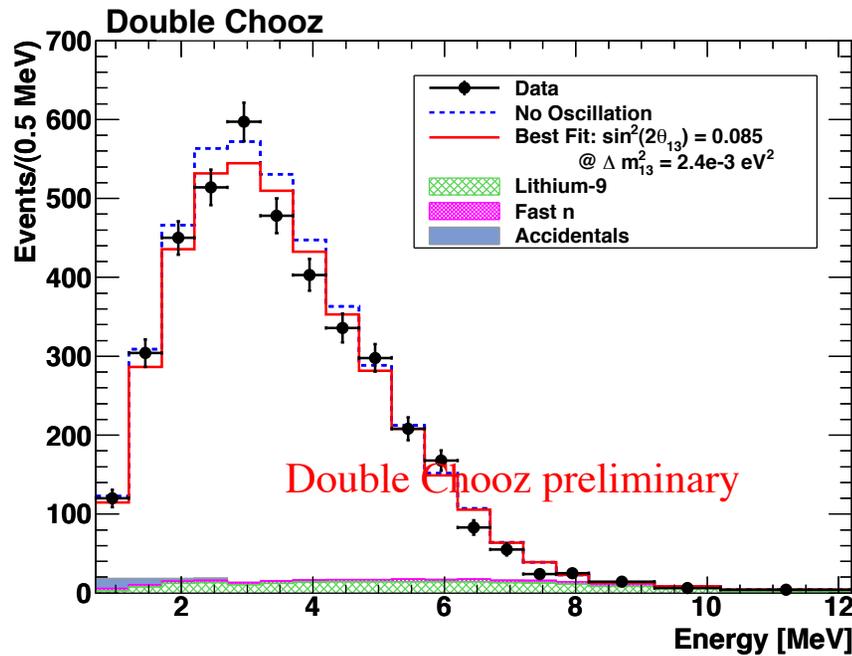
M_{ij}^{detector} - detector covariance matrix

M_{ij}^{stat} - statistical covariance matrix

Σ_{ij}^b - background covariance matrices

P_R, P_b - Pull terms that allow reactor and background normalization systematics to be varied within their error ranges.

Oscillation Search Result



Rate Only :

$$-\sin^2(2\theta_{13}) = 0.096 \pm 0.029(\text{stat}) \pm 0.073(\text{syst})$$

Shape Only :

$$-\sin^2(2\theta_{13}) = 0.044 \pm 0.157$$

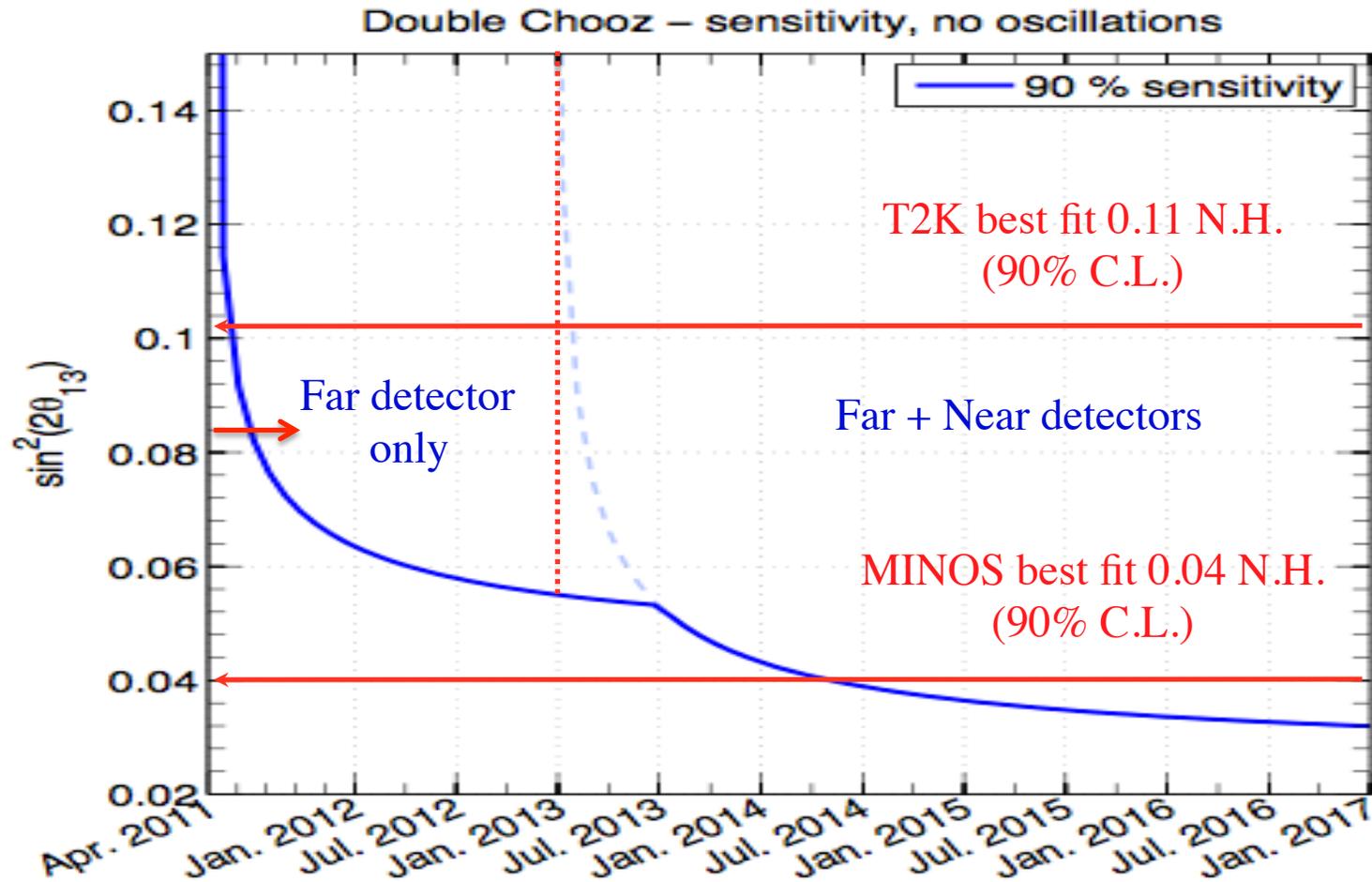
Rate & Shape :

$$\sin^2(2\theta_{13}) = 0.086 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$$

-No-Oscillation Excluded at 92.1 %

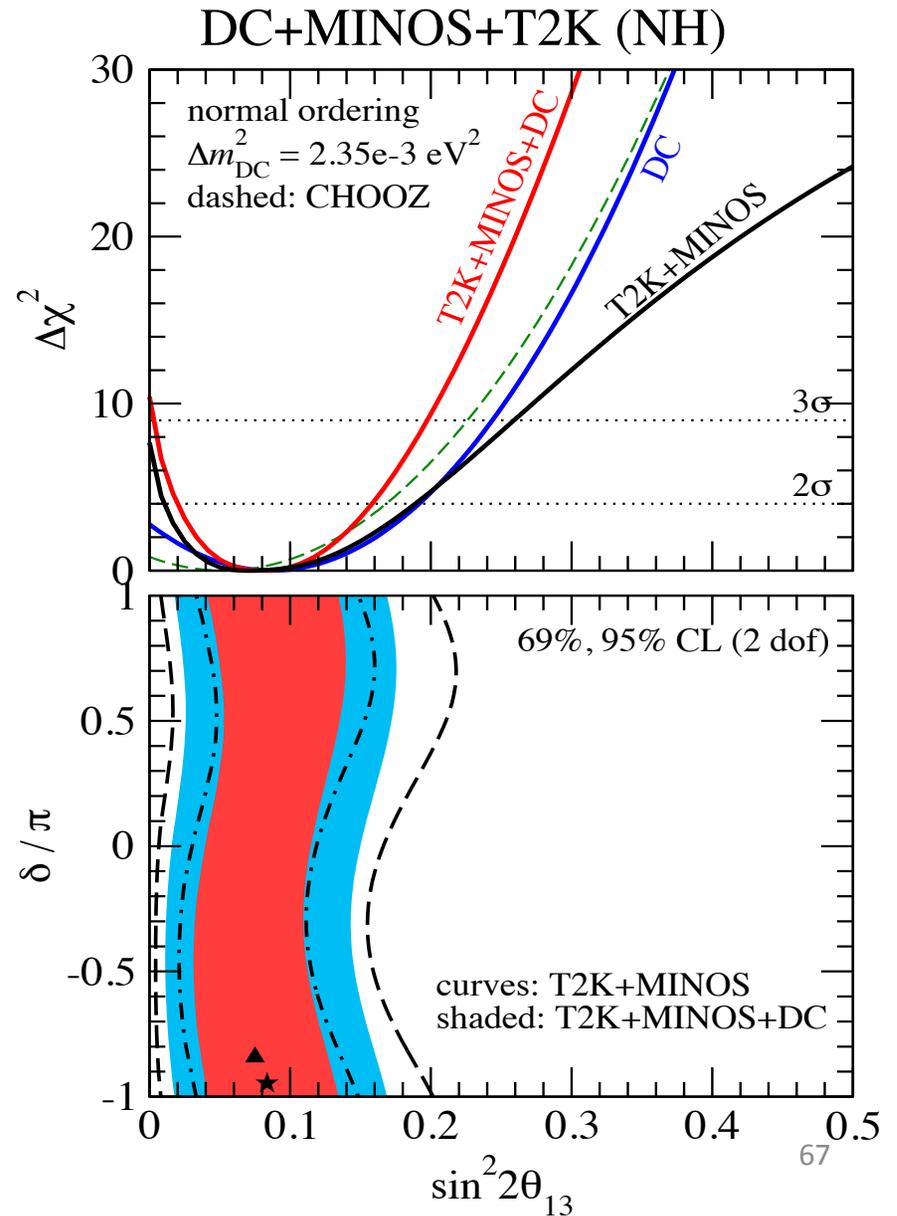
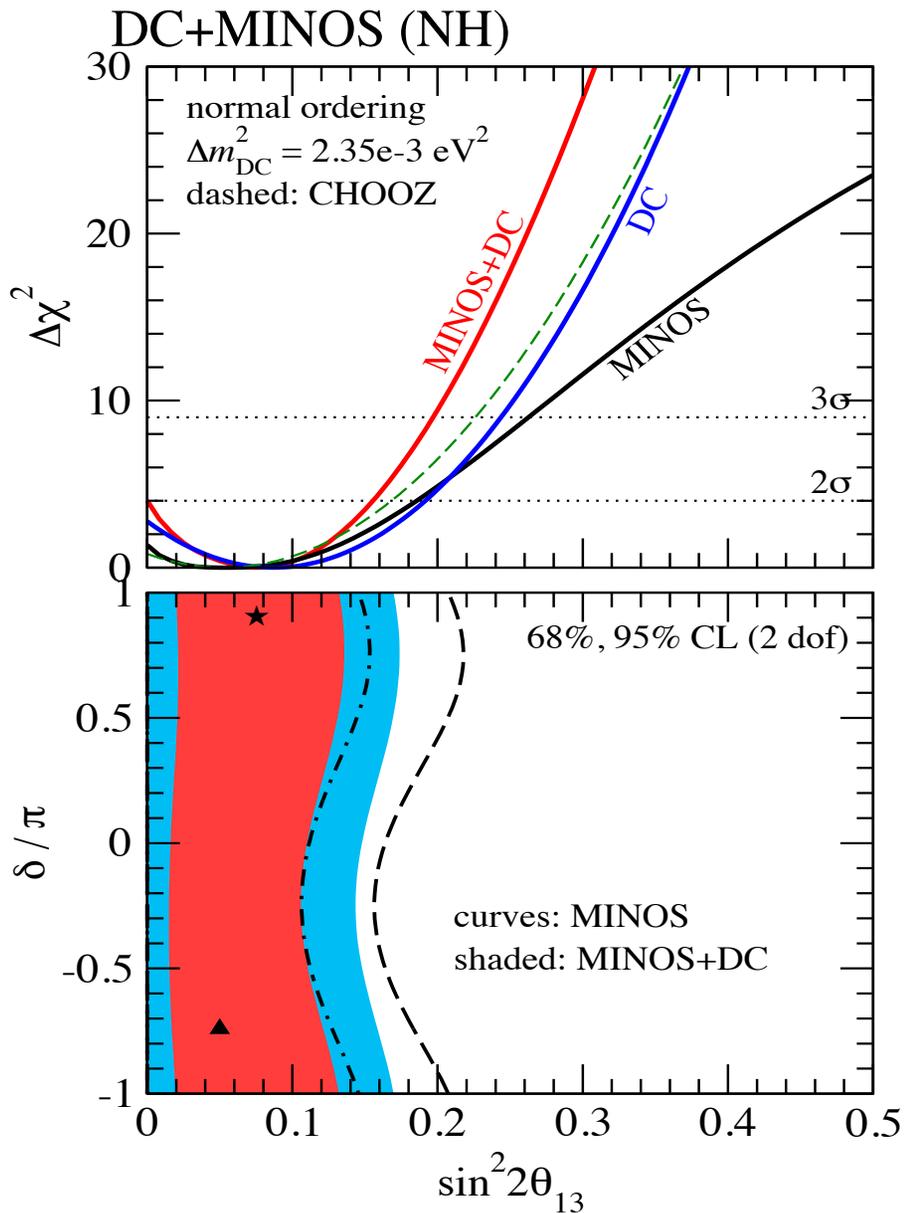
Double Chooz Prospects

-Timeline and sensitivity



Combination of Double Chooz, MINOS and T2K

-Combination of recent θ_{13} searches.



Note on effective Δm^2 difference

-From Thomas Schwetz:

-Using H. Nunokawa, S. J. Parke and R. Zukanovich Funchal, Phys. Rev. D 72 (2005) 013009, arXiv:hep-ph/0503283:

$$\Delta m_{ee}^2 = \Delta m_{\mu\mu}^2 \pm \Delta m_{21}^2 (\cos 2\theta_{12} - \cos \delta \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23})$$

$$\Delta m_{\mu\mu}^2 = 2.32_{-0.08}^{+0.12} \times 10^{-2} \text{ eV}^2 \quad \text{MINOS: P. Adamson et al. [The MINOS Collaboration], Phys. Rev. Lett. 106 (2011) 181801, arXiv:1103.0340 [hep-ex]}$$

$$\Delta m_{21}^2 = 7.50_{-0.20}^{+0.19} \times 10^{-5} \text{ eV}^2, \quad \tan^2 \theta_{12} = 0.444_{-0.030}^{+0.036} \quad \text{KamLAND: A. Gando et al. [The KamLAND Collaboration], Phys. Rev. D 83 (2011) 052002, arXiv:1009.4771 [hep-ex]}$$

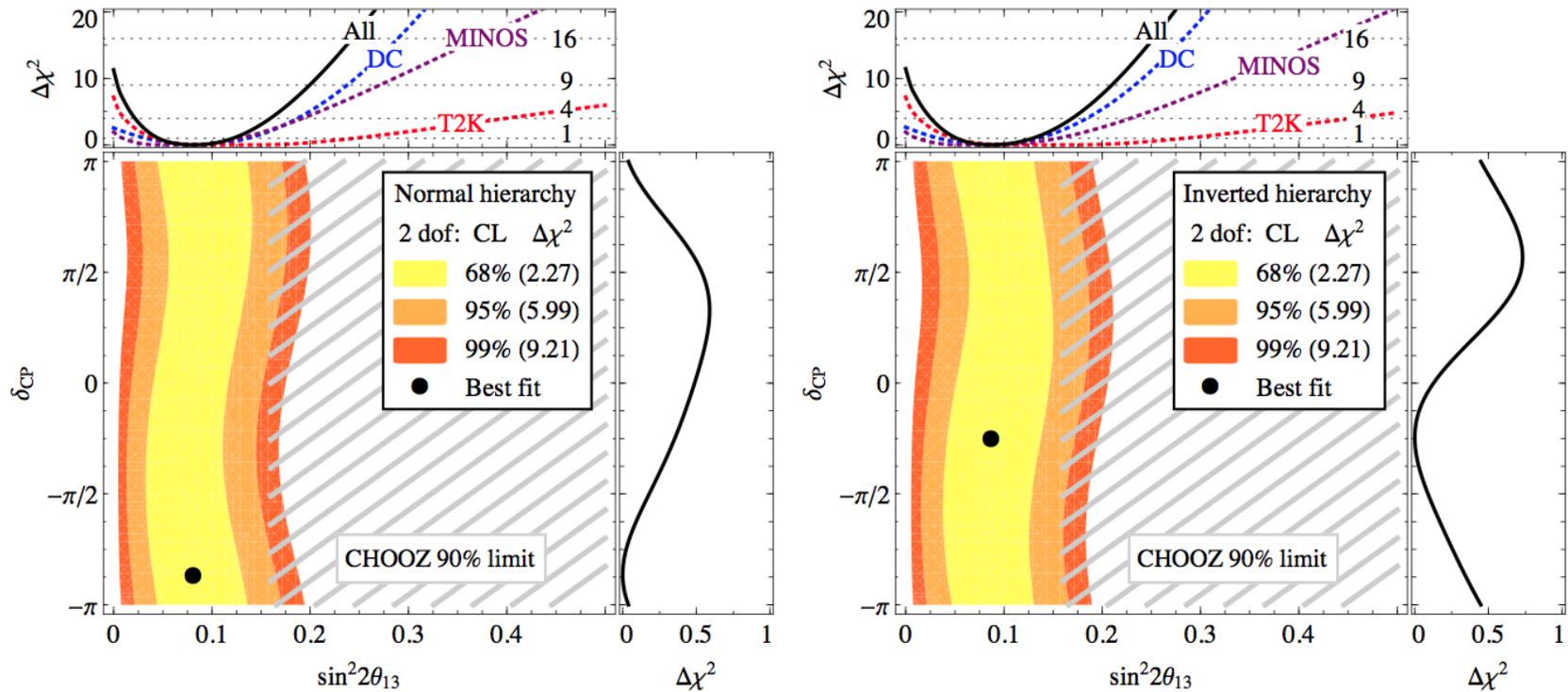
Use $\sin^2 2\theta_{13} = 0.1$ and $\tan \theta_{23} = 1$ to get $\sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23} \approx 0.15$

$$\Delta m_{ee}^2 = \begin{cases} 2.35 \\ 2.29 \end{cases} \times 10^{-2} \text{ eV}^2 \quad \begin{array}{l} \text{(normal)} \\ \text{(inverted)} \end{array}$$

Δm^2 difference relevant for Double Chooz.

Combination of Double Chooz, MINOS and T2K

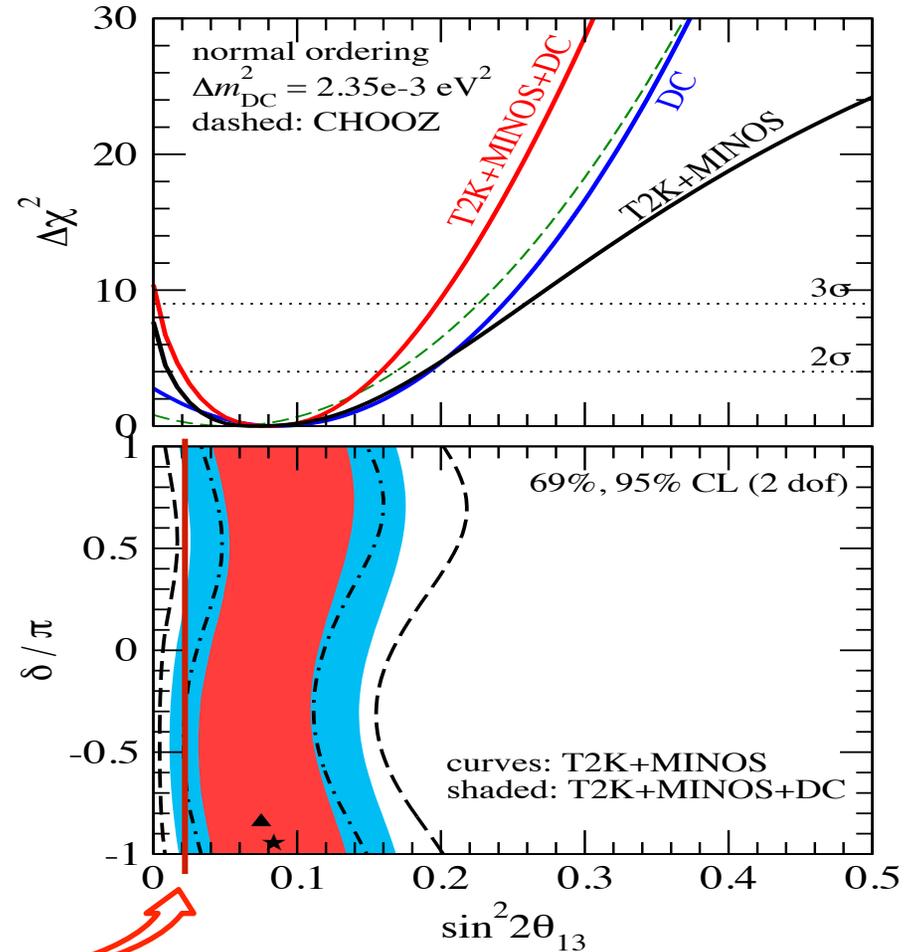
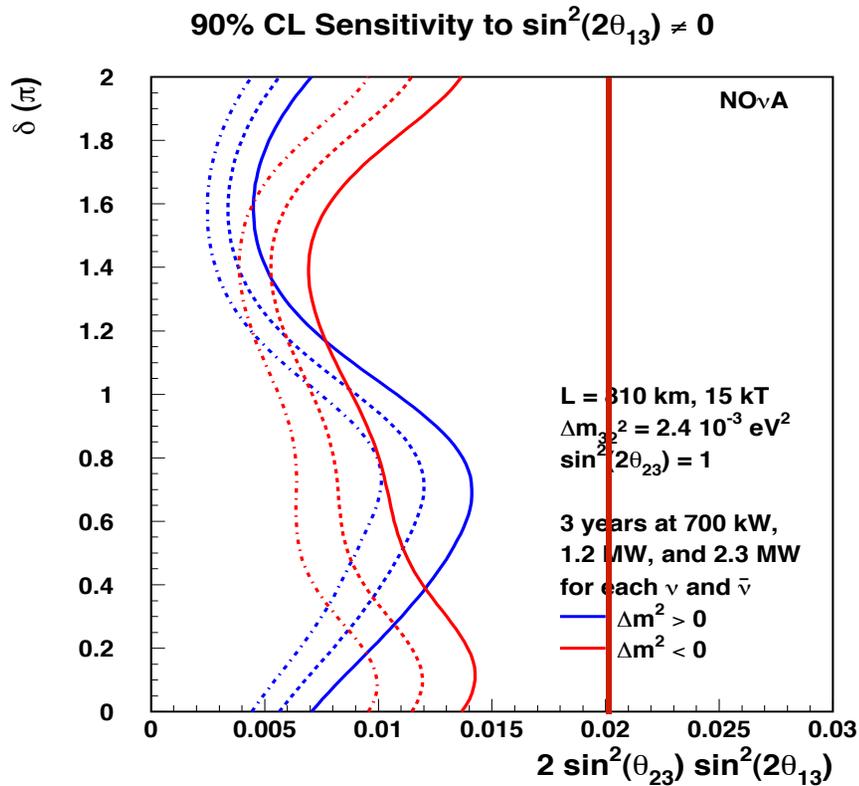
-Combination of recent θ_{13} searches.



Result from “Combining Accelerator and Reactor Measurements of θ_{13} : The First Result.”
 P.A.N.Machado, H.Minakata, H.Nunikawa, R.Zukanovich Funchal, arXiv:1111.3330[hep-ph].

What if θ_{13} is large?

- Opportunity for leptonic CPV searches and mass hierarchy determination in the long-baseline ν oscillation experiments.
- NOvA Sensitivity:



Summary

- Double Chooz is running as designed.
- Reported analysis of 5 months of data with far detector only.
- Hint for positive value of θ_{13}
 - $\sin^2(2\theta_{13}) = 0.086 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$
 - No-Oscillation excluded at 92.1% CL
- The near detector will be operational by early 2013.
- Great prospect towards precise measurement θ_{13} with 2 nuclear cores
 - Simple site configuration. Reactor Off-Off periods offer in-situ background measurement
 - Comprehensive set of Calibration Systems
- Global fits with (MINOS, T2K) indicate $\sin^2(2\theta_{13}) \neq 0$ at 3σ .
- Measurement of $\sin^2 2\theta_{13} > 0.01$ is key to planning leptonic CPV searches and mass hierarchy determination in long-baseline ν oscillation experiments.
- Opportunities for NO ν A, LBNE.